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Drainage of organic soils and GHG emissions: Validation with country data

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Abstract. Drainage of large areas with organic soils was conducted over the past century to free land for agriculture. A significant acceleration of such trends was observed in recent decades in South-East Asia, largely driven by drainage of tropical peatlands, an important category of organic soils, for cultivation of oil palm. This work presents methods and main results of
10 a new methodology developed for FAOSTAT, whereby the overlay of dynamic maps of land cover and the use of information on histosols allows the production of a global annual dataset of drained area and emissions over a time series, covering the period 1990–2019. This is an improvement over the existing FAO approach, which had produced only a static map of drained organic soils for the year 2000. Results indicate that drained area and emissions increased by 13 percent globally since 1990, reaching in 2019 24 million ha of drained organic soils, with world total emissions of 830 million tonnes of carbon dioxide
15 (CO_2) equivalent. Of these totals, the largest contribution was from the drainage of tropical peatlands in South-East Asia, generating nearly half of global emissions. Results were validated against national data reported by countries to the UN Climate Convention and to well-established literature. Overall, the validation yielded a good agreement with these sources. FAOSTAT estimates explained about 60 percent of the variability in official country reported data. The predicted emissions were virtually identical – with over 90 percent of explained variability – to official data from Indonesia, currently the top emitting country
20 by drained organic soils. Also, calculated emissions factors for oil palm plantations in Indonesia and Malaysia were in the same range and very close to emissions factors derived from detailed field measurements. This validation suggests that the FAO estimates may be a useful and sound reference in support of countries reporting needs. Data are made available as open access via the Zenodo portal (Tubiello and Conchedda, 2020) with DOI 10.5281/zenodo.3942370.

1 Introduction

25 Organic soils are, generally speaking, wet soils ecosystems, characterized by high levels of organic matter, which accumulates in large quantities under the anoxic conditions that exist in the presence of water. They include tropical peatlands, high-latitude bogs and mires. Indeed, while organic soils cover globally a mere 3 percent of the terrestrial land area, they represent up to 30 percent of the total soil carbon, playing an important role in maintaining the earth's carbon balance (FAO, 2020a). Drainage of organic soils releases large quantities of carbon dioxide (CO_2) and nitrous dioxide (N_2O) into the atmosphere, as a result of
30 the increased oxidation and decomposition rates of the underlying organic matter once water is removed. These emissions

typically last for several decades after the drainage event, due to the large quantities of organic substrate available. Agriculture is a major cause of drainage of organic soils around the world, and especially since 1990 due to the cultivation of permanent crops such as oil palm. Restoration of degraded organic soils is currently a priority in several countries as part of their greenhouse gas mitigation and ecosystem restoration commitments under the UN climate convention (Leifeld and Menichetti,

35   2018; Tiemeyer et al., 2020). Measuring current trends, globally and with country detail, is therefore important to identify and quantify existing and fast-developing new hotspots of degradation and to help reduce emissions from drained organic soils in future decades. Estimates of drainage area and greenhouse gas (GHG) emissions from organic soils for the year 2000 were developed by FAO and used by the Intergovernmental Panel on Climate Change (IPCC) for global analysis (Tubiello et al., 2016; Smith et al., 2014). That preliminary work was based on the geospatial overlay of two static maps, one for land cover,

40   indicating presence of agriculture, and one for soil characteristics, indicating presence of organic soils, through the use of histosols as proxy. This paper describes additional methodological developments made possible by the availability of time dependent land cover maps, resulting in the production, for the first time, of estimates over a complete time series (1990–2019).

2 Material and Methods

45   Organic soils are characterized by high concentrations of organic matter. They mostly develop under poorly drained, wetland conditions and are found at all altitudes, with the vast majority occurring in lowlands (Rieley and Page, 2016). Peatlands are an important type of organic soils (Page et al., 2011; IPCC, 2014a). According to IPCC (2006), organic soils can be largely identified with the *histosols* group of the FAO-UNESCO classification. FAO and Wetlands International (2012) indeed described *histosols* as soils that develop in (predominantly) "moss peat in boreal, arctic and subarctic regions, *via* moss peat,

50   reeds/sedge peat and forest peat in temperate regions to mangrove peat and swamp forest peat in the humid tropics". Common names for *histosols* are `peat soils', `muck soils', `bog soils' and `organic soils' (FAO et al., 1998). In this work, we follow IPCC guidelines and identify organic soils with histosols. Cropland and grassland organic soils are drained permanently or semi-permanently, as well as regularly limed and fertilized, to permit annual or permanent crop cultivation, including tree plantations, or to support livestock grazing. For these reasons, the presence of cultivated crops or grazing animals on organic

55   soils (Noble et al., 2018) —which have otherwise low productivity—may be associated with drainage, causing N and C losses and overall degradation (Martin et al., 2013). Peat emissions are unique in that they continue emitting for long periods after the initial drainage (FAO, 2020).

Area of drained organic soils and associated greenhouse gas (GHG) emissions were estimated following default Tier 1

60   methods of the IPCC (2006) over IPCC land use classes *Cropland* and *Grassland* (corresponding to FAO land use classes ''Cropland'' and ''Land under permanent meadows and pastures''). This methodology was already applied within

FAOSTAT (Tubiello et al., 2016) and was extended herein by introducing a time-dependent component, as follows in Eq. (1):

$$Emissions_{y,i,j} = \sum_{y,j} A * EF_{i,j,k} \qquad \text{Eq. (1)}$$

65

where:

$Emissions_{y,i,j}$ = Emissions for year y of greenhouse gas i = N_2O, CO_2 over land use type j = cropland, grassland;

$\sum_{y,j} A$ = Total area for year y of drained organic soils under land use type j = cropland, grassland;

EF_{ijk} = Emissions Factors, emissions per unit area of drained organic soils of greenhouse gas i, land use type j and

70   climatic zone k;

y = Years in the period 1992–2018 as yearly time-steps representing time-dependent land cover maps;

k = Boreal, temperate, tropical climatic zones, following IPCC (2006).

At pixel level, the work we carried out included the use of a geospatially-detailed map of organic soils, annual maps of land
75 cover, a livestock density map and a map of climatic zones. The area drained for cropland and grassland organic soils represent
the time-dependent components of Eq. (1). They were calculated as follows:

$$A_{cropland,y} = LU_{cropland,y} * WMS_{histosols} \qquad \text{Eq. (2)}$$

80          $$A_{grassland,y} = LU_{grassland,y} * WMS_{histosols} * LDR_{>0.1} \qquad \text{Eq. (3)}$$

Where:

$A_{cropland\_y}$; $A_{grassland\_y}$ = Area of drained organic soils on cropland and grassland, for the year y obtained as the overlay of

$LU_{cropland,y}$; $LU_{grassland,y}$ = Area, for the year y under IPCC and FAO land use class ''cropland'' and "grassland",
85   derived from land cover classes (cropland or grassland) in global land cover maps of the year y;

$WSM_{histosols}$ = Area with soil type *histosols* from the Harmonized Soil Map of the World (FAO and IIASA, 2012).
Following IPCC (2006), *histosols* are used as proxy for organic soils;

$LDR_{>0.1}$ = For grassland organic soils only, area with livestock density of ruminants (in livestock units) above a
defined threshold, derived from global maps of the FAO Gridded Livestock of the World (Robinson et al., 2014), to
90   identify grazed grassland.

The IPCC basic methodology for carbon (C) and nitrous oxide (N_2O) emissions estimates from organic soils assigns an annual
EF (i.e. quantity of gas emitted per ha and per year per unit of activity data) associated with the loss of these gases following

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the drainage for agriculture. Drainage stimulates the oxidation of organic matter previously built up under a largely anoxic
95   environment. The rates of emissions are influenced by climate, with warmer climates accelerating the processes of oxidation
of soil organic matter hence causing higher emissions than in temperate and cooler climates. The emission factors by gas thus
are climate-dependent. In this methodology, we spatialized the relevant IPCC emission factors following a global map of
climatic zones (JRC, 2010) to produce global maps EF for the two gases. The pixel-computations then multiply the area of
drained and managed organic soils from Eq. (2) and Eq. (3) above by global maps of emission factors to derive estimates of
100   annual N_2O and CO_2 emissions by pixel as summarized in Eq. 1.

As described in Tubiello et al., (2016), the approach is based on reclassification tables to extract the proportions of cultivated
and grassland area from the yearly land cover maps. When all input layers overlap, the underlying assumption is that of an
equal likelihood within each pixel to find cultivated (or grassland) area and organic soils. Operationally, the methodology
multiplies the area of organic soils in the pixel by the area of the pixel that is cropped or has grassland cover. In this way, we
105   derived by pixel the area of organic soils that is drained for agricultural activities. Organic soils must be indeed be drained to
allow for crop cultivation activities. In the case of grassland, livestock grazing beyond the carrying capacities of organic soils
leads instead to peat degradation and drainage. The following sections provide more details about the information necessary
to implement the computations above.

2.1 Soils

110   Information on the geographical distribution of *histosols*, for use in the term WSM of Eq. (2) and Eq. (3) above, was derived
from the Harmonized World Soil Database (HWSD v 1.2), a raster dataset with a nominal resolution of 30 arc second on the
ground (corresponding approximately to 1 x 1km at the equator) published in 2012 by FAO and the International Institute for
Applied Systems Analysis (IIASA). The HWSD compiles more than 40 years of soil information from several sources
worldwide, re-classified and harmonized according to the FAO-UNESCO classification. The standardized structure of the
115   HSWD v 1.2 allows displaying and querying the composition in terms of soil units and of soil parameters such as the organic
carbon content, the pH, or the water storage capacity. The HSWD dataset was queried to extract values representing the
percentage of the pixel area that contains histosols, as either dominant or secondary soil type (Fig. 1).

2.2 Land cover and land use

120   Information on the area extent of IPCC categories *cropland* and *grassland* for use in terms $LU_{cropland}$ and $LU_{grassland}$ in Eq. (2)-
(3) was taken from the land cover maps produced by the Catholic University of Louvain (UCL) Geomatics (UCL Geomatics,
2017), produced under the Climate Change Initiative of the European Spatial Agency (ESA CCI, 2020) and hereinafter referred
to as CCI LC maps. The CCI LC maps were first released in April 2017 as 24 global annual and consistent land cover maps
covering the period 1992 to 2015 (UCLouvain Geomatics, 2017). At the end of 2019 and in the framework of the European

125   Copernicus Climate Change Service (C3S, 2019), three new global land cover (LC) products were released for the years 2016, 2017 and 2018 that are consistent with earlier maps (Fig. 2).

The long-term consistency of this dataset, yearly updates and high thematic detail on a global scale make it uniquely suitable to observe and assess changes in area drained and GHG emissions from organic soils. The CCI LC maps contain information
130   for 22 global land cover classes, based on the FAO Land Cover Classification Systems (Di Gregorio, 2005), with a spatial resolution of approximately 300m.

The land cover maps (1992–2018) were used to assign to each pixel the proportion of its area under relevant land cover categories. This information was combined to provide proxy information on the proportion of pixel area under land cover / land use classes *cropland* and *grassland* (Tables 1 and 2).

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2.3 Livestock

Information on the spatial distribution of livestock for use in estimating the term LDR in Eq. (3) above, was taken from the Gridded Livestock of the World (GLW)(Robinson et al., 2014), providing geospatial data on the density of three ruminants species: cattle, sheep and goats (Fig. 3). Animal numbers by pixel were first converted in livestock units (LSU)(FAO, 2011),
140   and pixels with values higher than 0.1 (Critchley et al., 2008; Worrall and Clay, 2012) selected for use in Eq. (3).

2.4 Climatic Zones and emission factors

As discussed above, pixel-level climatic information for use in terms EF_{ijk} in Eq. (1), was derived from a map of climatic zones. The Joint Research Centre (JRC) of the European Commission, developed this spatial layer in line with IPCC specifications based on latitude and elevation of each pixel (Figure 4).
145   Default IPCC emissions factor by land use and gas (Table 3) were then assigned by pixel to each climatic zone and three additional geospatial layers were produced to cover possible combinations of EFs (

Figure 5). As one country may encompass more than one climatic zones, when emissions are aggregated at national level, the resulting emissions factors represent weighted averages of the various EFs assigned at pixel level. In computations, CO_2-C losses are converted to CO_2 values multiplying by 44/12 while N_2O emissions are calculated multiplying N_2O-N values by
150   44/28.

2.5 Data Availability: Structure of the FAOSTAT datasets on ''Organic Soils" and online access

Results from the spatial computation are aggregated at national level for 101 countries and 4 territories, representing the subset of FAOSTAT countries and territories where organic soils are present. Statistics are disseminated in three separate FAOSTAT domains (FAO 2020b,c,d), over the period 1990–2019, in line with country reporting requirements to the Climate Convention

155 and following the IPCC (2006). Namely, statistics are disseminated by gas and land use class: emissions of N_2O on cropland and grassland are disseminated under the domain Cultivation of Organic soils (FAO, 2020b) of FAOSTAT Emissions-agriculture; whereas emissions of CO_2 on Cropland (FAO, 2020c) and Grassland (FAO, 2020d) are disseminated within the FAOSTAT Emissions-Land use domain. As part of ongoing efforts to provide users with reliable and transparent data, the complete spatial dataset that underlies FAOSTAT statistics will be also disseminated through FAO new maps catalog (FAO,

160 2020e). Under the dataset, Cultivation of Organic soils, N_2O emissions are also disseminated in CO_2eq by applying three different sets of Global Warming Potential (GWP) coefficients (100-year time horizon) from the IPCC assessment reports: *a)* IPCC Second Assessment Report (IPCC, 1996); *b)* IPCC Fourth Assessement Report (IPCC, 2007); and *c)* IPCC Fifth Assessment Report (IPCC, 2014b). All data are also available at Zenodo as open access (Tubiello and Conchedda, 2020) with DOI 10.5281/zenodo.3942370. They and can be downloaded at https://zenodo.org/record/3942370#.XxWJjygzbIU.

165 **2.6 Limitations and uncertainty**

Previous work had estimated the uncertainty of our estimates at ±40% for the area information and an uncertainty range (−14%, +166%) for the emission estimates. These uncertainties, valid at pixel level, were assumed to also characterize the nationally-aggregated values (Tubiello et al., 2016). Furthermore, the new methodology developed herein may result in some cases in reduction in the drained area during the 30 years of the analysis (see Appendix A, Table A1). In such cases, the pixel-level

170 proportions that are applied to identify the cropland and grassland cover, have detected corresponding changes in land cover. The scale of the analysis prevents however to understand whether these changes actually happened in the area of organic soils thus resulting in a rewetting of the drained peats or are instead an artefact of the spatial methods. The IPCC Wetlands Supplement introduced already in 2014 additional methodological guidance, with a specific focus on the rewetting and restoration of peatland that was not included in the 2006 Guidelines (IPCC, 2014a). Limited country-specific activity data on

175 rewetting prevented however implementing the Supplement refined methods in the FAOSTAT dataset.

3 Main results: Global trends

In 2019, nearly 25 Mha or about 7.5 percent of the 328 Mha of worldwide *histosols* had been drained for agriculture with a limited increase since 1990. Data suggest that the largest extent of organic soils in Northern America and Eastern Europe have undergone little changes during the past decades likely because these peats have been drained for agriculture already for many

180 centuries (Joosten and Clarke, 2002). The drainage of organic soils is instead a more recent phenomenon in South East Asia. In this region, the drained area grew by 5 percent points since 1990 and in 2019 more than 26 percent of the original organic soils were already drained. Asia is on average the region with the highest share of drained *histosols (*30 percent) while, at sub-regional level Western Europe had over two thirds of its organic soils that were drained already in 1990. In 2019, among countries where the area of *histosols* is above 1Mha (see Annex A, Table A1), the larger proportions of drained organic soils

185   were in Mongolia (over 80 percent), Germany (75 percent), Poland (60 percent), United Kingdom and Belarus (about 50 percent). Nearly one fourth of the original extent was drained in Indonesia and Zambia and 30 percent in Malaysia.

In 2019, Indonesia had the largest area of drained organic soils (newly 5Mha), followed by the Russian Federation (about 1.9 Mha) and the United States of America (nearly 1.6 Mha). Among these top ten countries, Indonesia and Malaysia also registered the largest relative increases in area drained since 1990 (+5 and +10 percent for Indonesia and Malaysia,

190   respectively).

Global GHG emissions from drained organic soils were 833 Mt CO_2eq. In 2019, emissions were 13 percent higher when compared to 1990 and 10 percent higher when compared to 2000 (Figure 6). This value represented almost 8 percent of total agriculture and related land use emissions.

In 2019, CO_2 and N_2O gas contributed 87 percent and 13 percent of global emissions. Grassland organic soils were

195   responsible for about 10 percent of all emissions while the vast majority was due to the drainage for cropping. These relative contributions have changed little since 1990 (Appendix A, Table A2).

In 2019, three-fourths of the global emissions from organic soils were from only 11 countries (Figure 7), Malaysia and Indonesia together were responsible for nearly half (47 percent) of total emissions.

4. Results: Data Validation

200   The FAOSTAT estimates of the extent of organic soils, which are used as input to Eq. (2)–(3), were compared to published data at country, regional and global level. Resulting emissions and emissions factors for oil palm plantations are also included to validate FAOSTAT results.

4.1 Area of organic soils and peatlands

Comparison of the extent of drained organic soils is hindered by a number of factors, including the fact that the FAOSTAT

205   data refers to area of organic soils, while a majority of published studies has focused on area of peatlands. The FAOSTAT global estimates of 3.3 million square kilometers (Mkm^2) of organic soils (*histosols*) were 25 percent smaller than the published range of 4.0-4.3 Mkm^2 of peat soils. This is consistent with statements by Xu et al. (2018), who highlighted that *histosols* tend to underestimate areas in tropical swamp-forested peatlands. At regional level, FAOSTAT data agreed well with the most recent estimates of Xu et al. (2018) and mean estimate from Immirzi et al. (Table 5). In addition, while acknowledging the

210   large differences existing between published estimates by regions, FAOSTAT estimates remained consistently within the observed ranges More specifically, FAOSTAT estimates of area of organic soils for North America was 1.3 Mkm^2 vs. a published range of 1.3 – 1.9 Mkm^2; for Asia, FAOSTAT estimated 0.3 Mkm^2 vs. a range of 0.3 – 1.5 Mkm^2; for Europe, FAOSTAT estimated 1.5 Mkm^2 vs. a range of 0.6 – 1.9 Mkm^2; for Africa, FAOSTAT estimated 0.07 Mkm^2 vs. a range of 0.05–0.2 Mkm^2; for South America, FAOSTAT estimated 0.1 Mkm^2 vs. a range of 0.09 – 0.5 Mkm^2; and for Oceania,

215   FAOSTAT estimated 0.05 Mkm^2 vs. a range of 0.00 – 0.07 Mkm^2.

We continued the validation analysis by comparing FAOSTAT estimates to published data for about 60 tropical countries, compiled from the widely recognized meta-analysis of Page et al. (2011), and for the same set of countries to values computed using a recent map of tropical peat distribution (Gumbricht et al., 2017)(Appendix B, Table B1). In 2017, Gumbricht and associates published new estimates of wetland and peatland areas, depths and volumes. The expert system approach is based

220 on three biophysical indices related to wetland and peat formation: (1) long-term water supply exceeding atmospheric water demand; (2) annually or seasonally water-logged soils; and (3) a geomorphological position where water is supplied and retained. At the aggregate level—the sum of area of organic soils in countries covered by Page et al. (2011)—the extent of tropical organic soils estimated by FAOSTAT was 0.43 Mkm2 , which compared well with the value of 0.44 Mkm^2 of Page, both about a third of the total in Gumbricht et al. (2017) (1.37 Mkm^2).

225 At country level, FAOSTAT estimates agreed well with data published by Page et al. (2011) (R=.677, p<0.001). For one percent increase in the area of histosols, the log-transformed model shows about 5.5 percent increase in the area of peat as mapped by Page and colleagues (R^2=.458) (Fig. 8). The largest differences were found in countries in South and Central America—where special formations at high altitudes and dry conditions, known as *paramos*, may be poorly captured as *histosols* (Lähteenoja et al., 2012). FAOSTAT and Page et al. (2011) data were in very close agreement for key global

230 contributors in Southeast Asia, Indonesia (0.20 vs. 0.21 Mkm^2) and Malaysia (0.02 vs. 0.03 Mkm^2).

FAOSTAT country-level estimates were, albeit to a lesser degree, also in good agreement with those obtained by aggregating geospatial information from Gumbricht et al. (2017) (R=0.541, p<0.0005). FAOSTAT histosols however explains only partially the variability in the peat area as mapped by these authors. (R^2=.293) (Fig. 9). For one percent increase in the area of histosols, the log-transformed model shows a 8 percent increase in the area of peat as mapped by Gumbricht et al. Significant

235 differences between FAOSTAT and this second, independent set of observed data included Brazil, where Gunbricht and colleagues (2017) estimated 0.31 Mkm^2 of organic soils, nearly forty times the area estimated in FAOSTAT and more than ten times the area published in Page et al. (2011); Peru, where Gumbricht et al. (2017) indicate some 0.08 Mkm^2, twice the FAOSTAT estimates and 0.02 Mkm^2 more than Page et al. (2011); and the Democratic Republic of Congo, where the new peatland map suggests a significant presence of organic soils (0.12 Mkm^2), consistently with recent studies (Dargie et al.,

240 2017), while FAOSTAT estimated only 240 km^2 and Page et al. (2011) less than 3000 km^2.

The use of observed or estimated data is hampered by the wide uncertainties that still exist in defining, mapping and measuring actual extent of peatland throughout the world. To date, no globally accepted definition of peatlands exists. To this end, ongoing international efforts such as the Global Peatlands Initiative (2020) are expected to improve and consolidate current knowledge.

4.2 Validation with country data reported to the Climate Convention of the United Nations

245 The FAOSTAT data uses Eq. (2)–(3) above to overlay information on organic soils extent with information on land use and other geospatial characteristics, to estimate the drainage area of organic soils due to agriculture (Tubiello et al., 2016). These were in turn used as input to estimate resulting GHG emissions. We used data reported by countries to the UN Framework

Convention on Climate Change (UNFCCC) for validation of these FAOSTAT estimates. We looked both at data from the National Greenhouse Gas Inventories of the Annex I Parties and to the national communication from Indonesia, a top emitter

250   country.

4.2.1 Annex I parties

UNFCCC data were available for thirty-eight countries belonging to the Annex I parties to the climate Convention. These represent developed countries, mostly located in temperate and boreal zones of the world. First, we compared data on the area drained (activity data), which allowed to test assumptions underlying the use of Eq. (2)–(3) above. FAOSTAT country-level

255   estimates were in good agreement with those officially reported by countries to the UNFCCC (R^2=0.57) of area drained of organic soils (Fig. 10). At regional level, FAOSTAT predicted a total of about 14 Mha of drained organic soils for Annex I parties, versus country reported figures of nearly 12 Mha for the last inventory in 2017 (Appendix B, Table B2). On the one hand, estimates in several countries with significant contributions were well in line with national reporting, including the United States of America (1.5 *vs* 1.4 Mha); Belarus (close to 1.4 Mha in both cases); Germany (1.1 *vs* 1.2 Mha). On the other,

260   significant differences were found in Poland (1.0 *vs* 0.7 Mha) and in the United Kingdom (1.3 *vs* 0.3 Mha). Wide differences also characterized two countries with major organic area extent, specifically the Russian Federation (1.8 *vs* 4.3 Mha) and Canada (1.3 *vs* 0.2 Mha). In these latter cases, differences have however opposite directions. FAOSTAT estimates were much larger than country reported data in Canada but smaller in the Russian Federation.

For the same set of UNFCCC countries as above, we also compared N_2O emissions, which are reported by countries under the

265   IPCC sector Agriculture. C fluxes from the drainage of organic soils are reported by Annex I countries under Land Use, Land Use Change, and Forestry (LULUCF) categories. In the inventories, relevant reporting categories are 4.B.1 "Cropland Remaining Cropland"; 4.B.2 "Land Converted to Cropland" and 4.C.1 "Grassland Remaining Grassland"; and 4.C.2 "Land Converted to Grassland". Data for carbon are much sparser than for N_2O emissions possibly due also to complexity in reporting (Berthelmes et al., 2015). Beside the differences in activity data (area drained) that were observed earlier, differences may also

270   due to countries applying Tiers higher than the default methodology applied in FAOSTAT as well as to the definition of types of land use causing drainage.

As for the area drained, FAOSTAT emissions estimates were also in good agreement with data officially reported to the UNFCCC (R^2=0.553) (Fig.11), but with FAOSTAT consistently overestimating country data. At regional level, FAOSTAT predicted total emissions of 184 kt N_2O for Annex I parties, versus country reported figures of 143 kt N_2O (Appendix B, Table

275   B2). Estimates of annual emissions in several countries with significant contributions were well in line with national reporting, including the United States of America (20 *vs* 27 kt N_2O); Belarus (19 *vs* 18 kt N_2O); Germany (14 *vs* 10 kt N_2O); and Ukraine (8 *vs* 6 kt N_2O). At the same time, significant differences characterized two countries with major organic area extent, specifically the Russian Federation (23 vs. 54 kt N_2O) and (16 vs. 0.2 kt N_2O).

FAOSTAT results are in line with other independent assessments, for instance a study for countries in the Baltic region

280   (Barthelmes et al., 2015) suggested that the area and emissions from drained organic soils are often underestimated in

UNFCCC reporting. In a recent paper, Tiemeyer et al. (2020) applied for Germany a refined methodology for organic soils in national GHG inventories using detailed activity data and IPCC Wetlands EFs. For a similar extent of drained organic soils (about 12 Mha) as in FAOSTAT, their emissions estimates from cropland and grassland drained organic soils were 45 Mt CO_2eq, about three-fold FAOSTAT results (14 Mt Mt CO_2eq). This suggests, that even FAOSTAT estimates may not fully
285   grasp the potential for mitigation from the rewetting of drained organic soils.

4.2.2 Non-Annex I parties

Over fourty percent of the global emissions from the agricultural drainage of organic soils is generated in Indonesia and Malaysia. In addition, these two countries have contributed the most to emissions increases since 1990 (FAO, 2020f) (Fig. 12).
290   We compared FAOSTAT estimates of GHG emissions from the drainage of organic soils in Indonesia to those reported by the country to the UNFCCC, over the period 2000–2016 in their second Biennial Update Report (BUR), submitted to the Climate Convention on December 2018. National reported data were based on a national map of peatland and on refined EFs from the Wetlands Supplement (IPCC, 2014a) and reported as distinct category "peat decomposition" under Forestry and Other Land Use (FOLU) emissions. Results indicated good agreement between FAOSTAT estimates and nationally reported
295   data. The average FAOSTAT GHG emissions over 1990–2016 were 281 Mt CO_2eq *vs* the 304 Mt CO_2eq reported by Indonesia to the UNFCCC. Both series have a similar upward trend and their agreement extended over the entire time series (R^2= 0.9446), albeit with increasing separation in the most recent years. This represents an additional validation of Eq. (2) and Eq. (3) in the methodology addressing the issue of time dependence in drainage data (Fig. 13). As FAOSTAT only includes drainage for agriculture, part of the differences may be due to the types of land use for which the BUR reports drainage and emissions, as
300   the BUR possibly includes drainage under forestry.

4.2.3 Emissions factors for palm oil plantations

The establishment of new oil palm plantations is recognized as main driver for the drainage of tropical peatlands in Indonesia and Malaysia (Hojer et., 2010; Hooijer et al., 2012; Miettinen et al., 2012; Dohong et al., 2018; Cooper et al., 2020; FAO, 2020f). As a supplementary validation of Eq. (1)–(2), we combined spatially the cropland land use layer to an additional map
305   of tree plantations produced by Petersen et al. (2016) (Fig. 14). These authors mapped the distribution of different types of plantations including oil palm –for the years 2012–2014 in seven countries: Brazil, Cambodia, Colombia, Indonesia, Liberia, Malaysia, and Peru, using satellite imagery and extensive field validation, particularly for Indonesia and Malaysia. This additional analysis allows to compare FAOSTAT resulting emissions factors (*i.e.* the emissions per unit area of oil palm on drained organic soils), to those in established literature.

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Peterson and associates estimated that oil palm plantations in Indonesia and Malaysia covered 11.7 Mha and 5.3 Mha in 2014, respectively. These were consistent with 2014 FAOSTAT statistics on oil palm harvested area, indicating 8.1 Mha and 4.7

Mha respectively for the two countries. Of these, based on our analysis of the crop drained soils and of the plantations map, about 9 percent (Indonesia) and 4 percent (Malaysia) were located in drained organic soils (Table 6). Together, the tree plantations mapped by Petersen and colleagues were responsible for almost half of the 2014 emissions from cropland organic soils in Indonesia.

In Malaysia, the relative contribution of oil palm plantations to the area drained for cultivation was even as nearly half of total area of crop organic soils and emissions in this country was due to oil palm plantations. Other types of plantations contributed an additional 10 percent to area drained and emissions, which suggests the contribution of annual and temporary crops to peat conversion in this country may less important than in Indonesia.

The EFs for oil palm plantations derived from the analysis was around 78 CO_2eq ha^{-1} yr^{-1} in the two countries, and in close agreement with published estimates (Table 10). Available literature is largely based on direct measurements and typically analyses the influence of the depth of drainage, soil subsidence rates, soil moisture and the period since the initial drainage and establishment of the oil palm plantations. Corresponding values range from minimum average losses of 13 t CO_2e ha^{-1} yr^{-1} as in Hashim et al., (2018) to a maximum value of 117 t CO_2e ha^{-1} yr^{-1} as in Matysek et al. (2018) and recent study by Cooper et al. (2020). FAOSTAT estimated EF is therefore very close to the average value from the selected studies (73 t CO_2eq ha^{-1} yr^{-1}). This additional validation confirms that our methodology is compatible with most relevant and well-established estimates of a major source of emissions from drained organic soils in South East Asia and suggests that FAOSTAT estimates may be equally applied to other tropical countries.

5 Conclusions

Organic soils are a rich carbon pool and their drainage for agriculture has important impacts on the global carbon cycle. FAOSTAT statistics on greenhouse gas emissions relative to the drainage of organic soils were updated for the period 1990–2019 based on geospatial computation and pixel-level application of default Tier I method of the Intergovernmental Panel on Climate Change (IPCC). In line with country reporting requirements to the Climate Convention, and following the IPCC, statistics are disseminated by gas (N_2O and CO_2) and land use classes, cropland and grassland in three separate FAOSTAT domains. These FAOSTAT statistics represent the only avaialble global dataset in the world today showing country, regional and global time series on drained organic soils. Efforts are also in progress to disseminate publicly the underlying spatial data.

In 2019, FAOSTAT estimated that nearly 25 million ha of organic soils were drained from agriculture and were responsible for 833 million tonnes of CO_2eq. This was about 8 percent of total agriculture and related land use emissions in that year. About half of the greenhouse gas emissions was due to the drainage of organic soils in South Eastern Asia and particularly Indonesia and Malaysia.

We validated methods and results by comparing data reported by countries to the United Nations Climate Convention on Climate Change including in the comparison both data from developed countries of the Annex I group and Indonesia, a top emitter country for drained organic soils. For this latter country we also validated with additional analysis the resulting emission

345   factor for oil palm plantations, a major driver of the emissions in South East Asia. FAOSTAT statistics are well aligned with country reported data and the most established literature. Overall, FAOSTAT statistics explained about 60 percent of the variability in official reported data. However, in Indonesia, the top emitter country by drained organic soils, as well as in many developed countries FAOSTAT statistics yielded an even higher agreement and proved a robust estimator of country official data. This suggests that the FAOSTAT database may provide a useful global reference in support of countries reporting

350   requirements while national capacities are being developed.

Following guidelines of the Intergovernmental Panel on Climate Change, FAOSTAT statistics are computed applying *histosols* as proxy for organic soils. However, wide uncertainties still remain as whether organic soils may fully capture the dynamics in peat distribution and related emissions particularly in tropical countries. FAO ongoing efforts under the Global Peatland Initiative are expected to provide advancements for mapping and monitoring peatlands worldwide.

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Tables

495

Table 1**. Proportion of area of relevant CCI-LC pixels corresponding to land use *cropland***

CCI-LC Class Code	CCI-LC Land Cover Class Label	Cropland Assigned pixel area (%)
10	Cropland rainfed	
11ᵃ	*Cropland, rainfed, herbaceous cover*	85%
12ᵃ	Cropland*, rainfed, tree or shrub cover*	
20	Cropland, irrigated or post-flooding	
30	Mosaic cropland (>50%) /natural vegetation (tree, shrub, herbaceous cover) (<50%)	60%
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	40%

ᵃ Corresponding to more detailed classification (Level 2) in CCI-LC maps but with limited geographical availability.

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Table 2. Proportion of area of relevant CCI-LC pixels corresponding to land cover *grassland*

CCI-LC Class Code	CCI-LC Land Cover Class Label	Grassland Assigned pixel area (%)
130	Grassland	100% herbaceous cover
140	Lichens and mosses	
120	Shrubland	
121[a]	*Evergreen shrubland*	
122[a]	*Deciduous shrubland*	
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	30% (20% herbaceous + 10% shrub cover)
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (< 50%)	40% (20% herbaceous + 20% shrub cover)
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	55% (30% herbaceous + 35% shrub cover)
110	Mosaic herbaceous cover (<50%) / tree and shrub (>50%)	80% (60% herbaceous + 20% shrub cover)
10	Cropland rainfed	5% natural herbaceous cover
11[a]	*Herbaceous crops*	

[a] Corresponding to more detailed classification (Level 2) in CCI-LC maps but with limited geographical availability.

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Table 3. **IPCC default emission factors assigned, by gas and climatic zone[a]**

Climatic zone	EF: CO2-C (t C ha^{-1} yr^{-1})		*Uncertainty*	EF: N$_2$O-N (kg ha^{-1} yr^{-1})		*Uncertainty*
	Cropland	**Grassland**		**Cropland**	**Grassland**	
1. Warm Temperate Moist	10	2.5		*8*		
2. Warm Temperate Dry						
3. Cool Temperate Moist						*Range 2 – 24*
4. Cool Temperate Dry						
5. Polar Moist						
6. Polar Dry	5	0.25		8[b]		
7. Boreal Moist			± 90%			
8. Boreal Dry						
9. Tropical Montane						
10. Tropical Wet	20	5.0		16		*Range 5 – 48*
11. Tropical Moist						
12. Tropical Dry						

510   [a] Adapted from table 5.6; Table 6.3 (for CO$_2$) and Table 11.1 (for N$_2$O) of IPCC (2006). [b] Default value not included in IPCC (2006), assumed equal to EF values for Cool Temperate zones.

515   Table 4. **Global Warming Potentials (GWP) relative to CO$_2$ (dimensionless)**

Greenhouse gas	GWP SAR (IPCC 1966)	GWP AR4 (IPCC, 2007)	GWP AR5 (IPCC, 2014)
N$_2$O	310	298	265

Table 5. **Comparisons of published global and regional estimates for area of peat / organic soils (km^2)[a]**

	Immirzi et al. (1992) mean	Lappalainen (1996) best estimate	Joosten and Clarke (2002) maximum	Xu et al., (2018)	FAOSTAT 2020
North America	1,710,470	1,735,000	1,860,000	1,339,321	1,311,595
Asia	338,208	1,119,000	1,523,287	283,861	258,686
Europe	1,784,887[b]	957,000	617,492	1,867,658[c]	1,501,696[c]
Africa	49,765	58,000	58,534	187,061	72,445
South America	86,271	102,000	190,746	485,832	99,860
Oceania	230	14,000	8,009	68,636	45,095
Total	**3,969,831**	**3,985,000**	**4,258,068**	**4,232,369**	**3,289,377**

[a] Adapted and extended from Rieley and Page (2016). [b] Immirzi et al (1992) estimates for Europe include the Soviet Union. [c]Xu
520 et al., 2018 and FAO estimates for Europe include the Russian Federation.

Table 6. **Contribution of oil palm and other tree plantations to area drained and emissions from crop organic soils, Indonesia and Malaysia in 2014**

	Mt CO_2	Mt N_2O	Mt CO_2eq	Share (%) of emissions from crop organic soils, by plantation type
Indonesia				
Oil palm	66.8	$23*10^{-3}$	72.8	23%
Oil palm mixed	10.1	$3*10^{-3}$	19.5	6%
Other tree plantations	58.2	$20*10^{-3}$	63.5	20%
All tree plantations	**76.9**	**$26*10^{-3}$**	**155.9**	49%
Malaysia				
Oil palm	16.3	$6*10^{-3}$	17.8	38%
Oil palm mixed	3.8	$1*10^{-3}$	4.1	9%
Other tree plantations	4.2	$1*10^{-3}$	4.6	10%
All tree plantations	24.3	$8*10^{-3}$	26.4	57%

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Table 7**. Comparison of EFs for oil palm plantations on organic soils from established literature and combined FAOSTAT / Petersen et al. (2016) spatial data**

Source	CO_2eq ha^{-1} yr^{-1}
Published studies	
Page et al., 2011	86−100
Hojer et al., 2012	78
Agus et al., 2013	43
Couwenberg and Hooijer, 2013	66
Hashim et al. 2018	13−53
Matysek et al., 2018	86−117
Cooper et al., 2020	70−117
FAOSTAT / Petersen et al., 2016	78

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Figures

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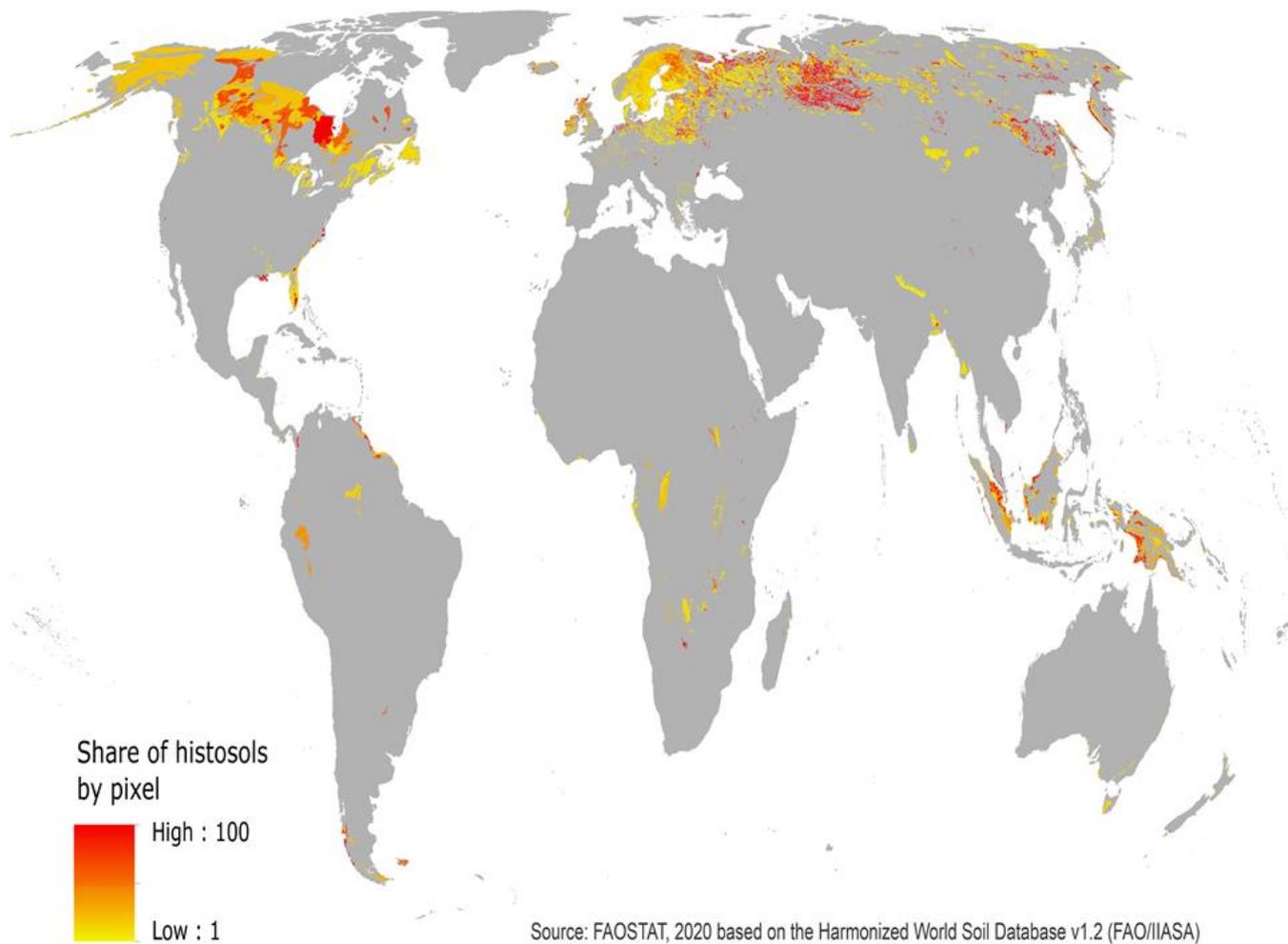
Figure 1. Global distribution of histosols, percentage of pixel area

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Cropland rainfed	Tree cover mixed leaf type (broadleaved and needleleaved)	Tree cover flooded/fresh brackish water
Cropland irrigated or post-flooding	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	Tree cover flooded saline water
Mosaic cropland (>50%) / natural vegetation (<50%)	Mosaic herbaceous cove (>50%) / tree and shrub (<50%)	Shrub or herbaceous cover flooded
Mosaic natural vegetation (>50%) / cropland (<50%)	Shurbland	Urban areas
Tree cover broadleaved evergreen (>15%)	Grassland	Bare areas
Tree cover broadleaved deciduous (>15%)	Lichens and mosses	Water bodies
Tree cover needleleaved evergreen (>15%)	Sparse vegetation (<15%)	Permanent snow and ice
Tree cover needleleaved deciduous (>15%)		

Source: FAOSTAT, 2020 based on the ESA CCI and Copernicus Climate Change Service Land Cover Maps

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Figure 2. Global land cover, 1992–2018 composite information from CCI-LC maps

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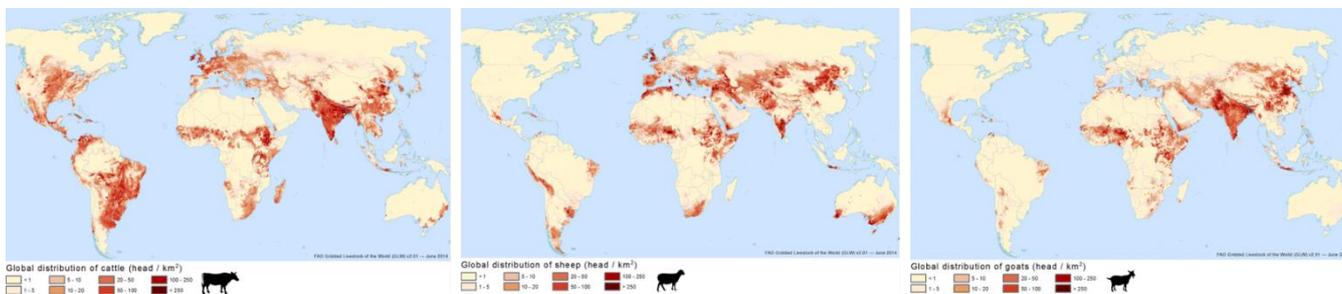
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Figure 3. Global distributions of cattle, sheep and goats, Gridded Livestock of the World (Robinson et al., 2014)
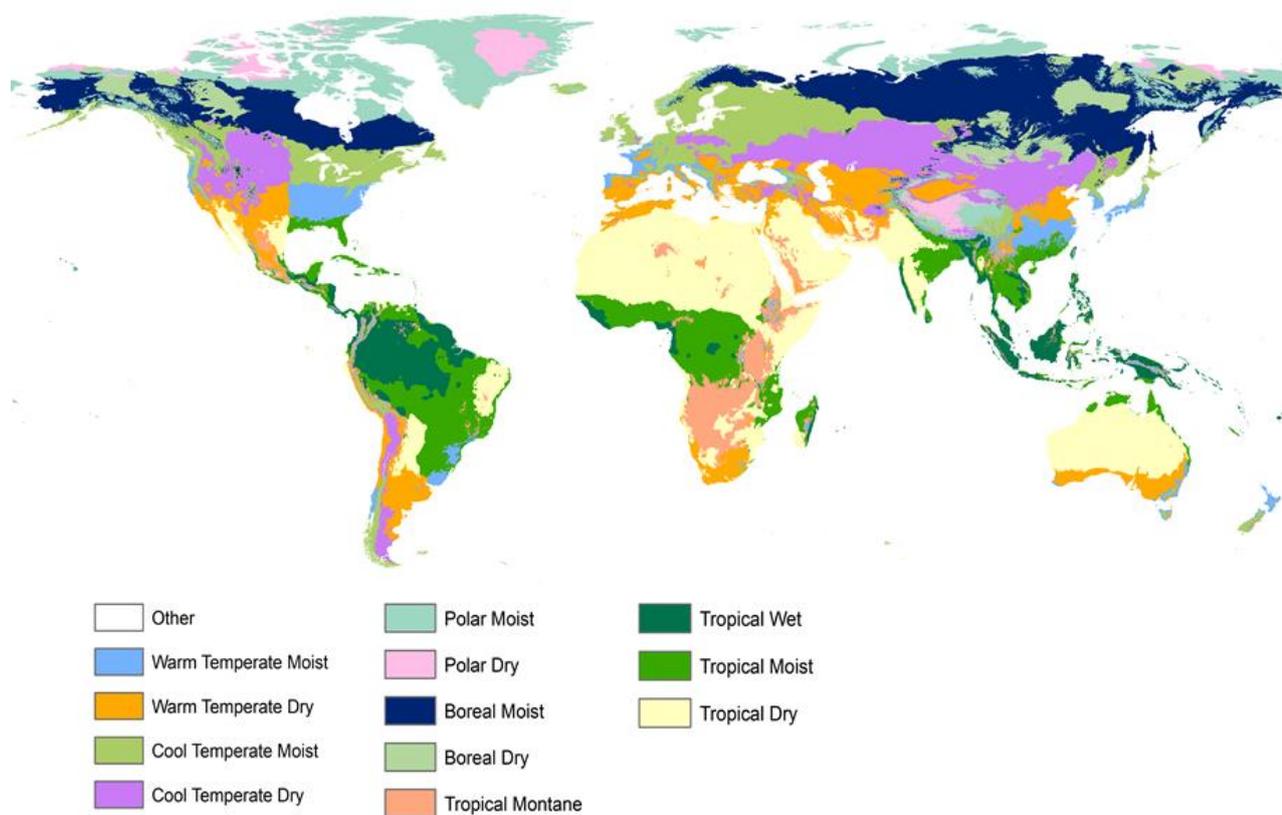
Source, FAO, 2020 based on IPCC climatic zones (JRC, 2010)

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Figure 4. Climatic zones based on IPCC classification (JRC, 2010)

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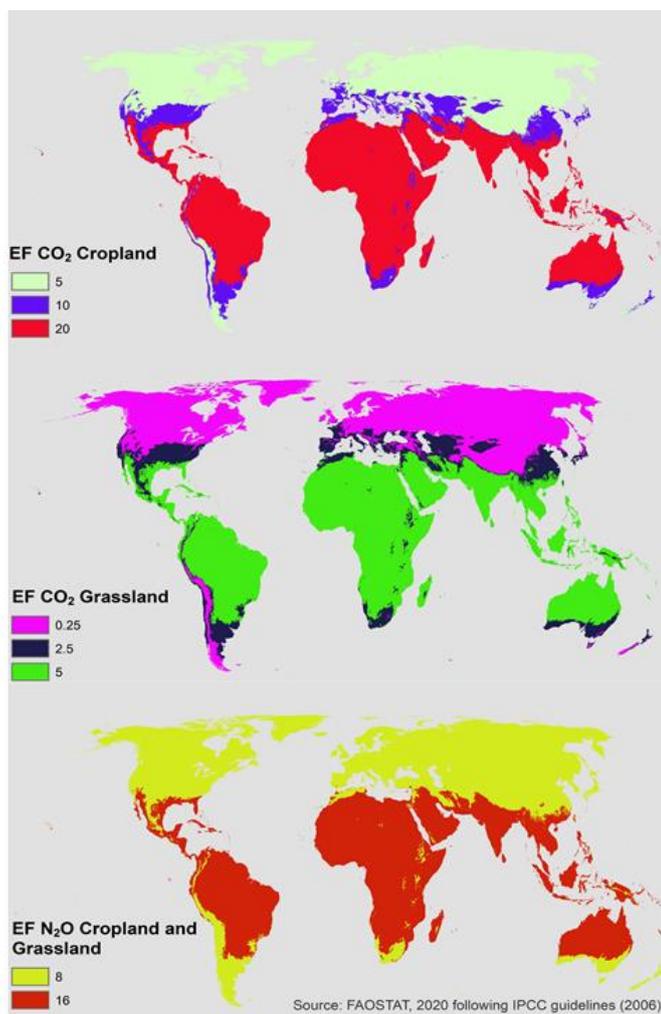
Figure 5. Spatial layers of emission factors by gas, land use and climatic zone

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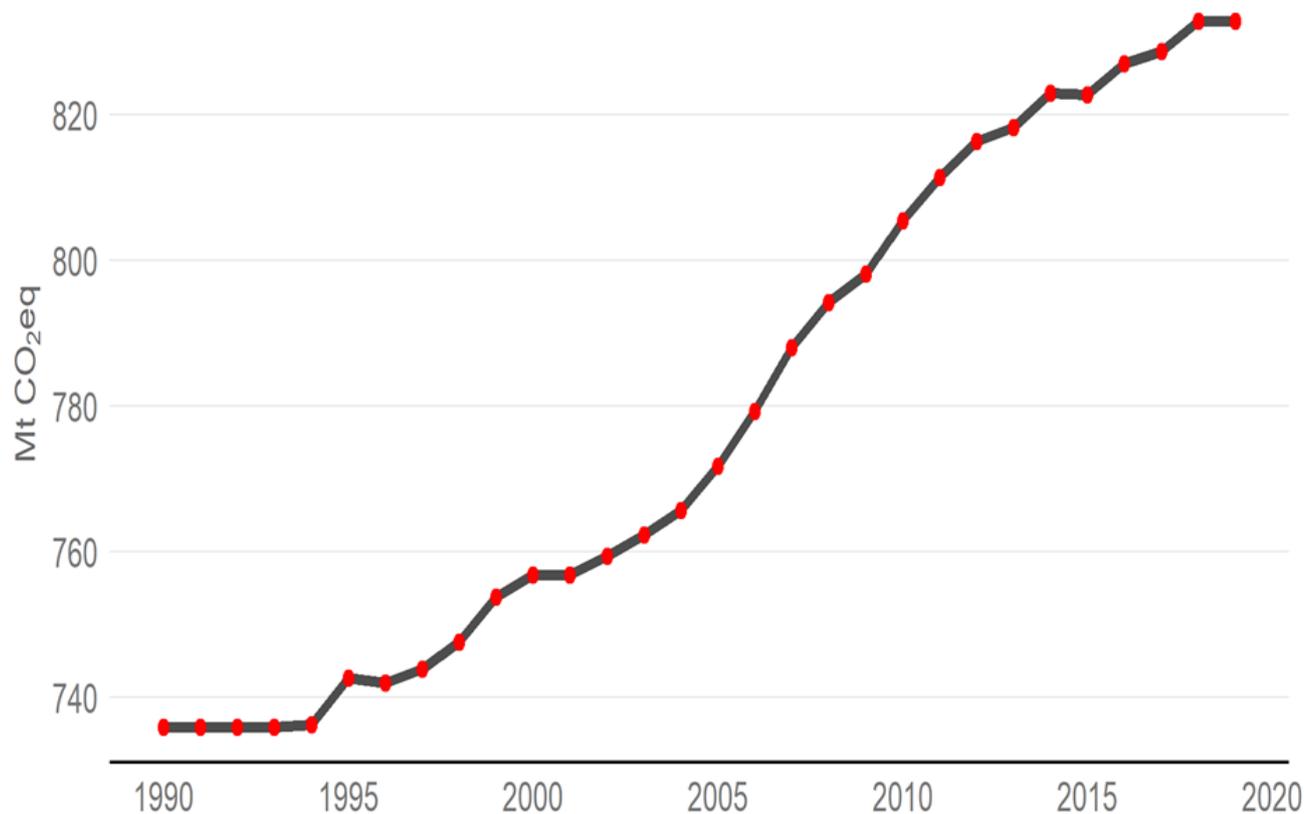
Source: FAOSTAT, 2020

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Figure 6. Global emissions from drained organic soils, 1990–2019
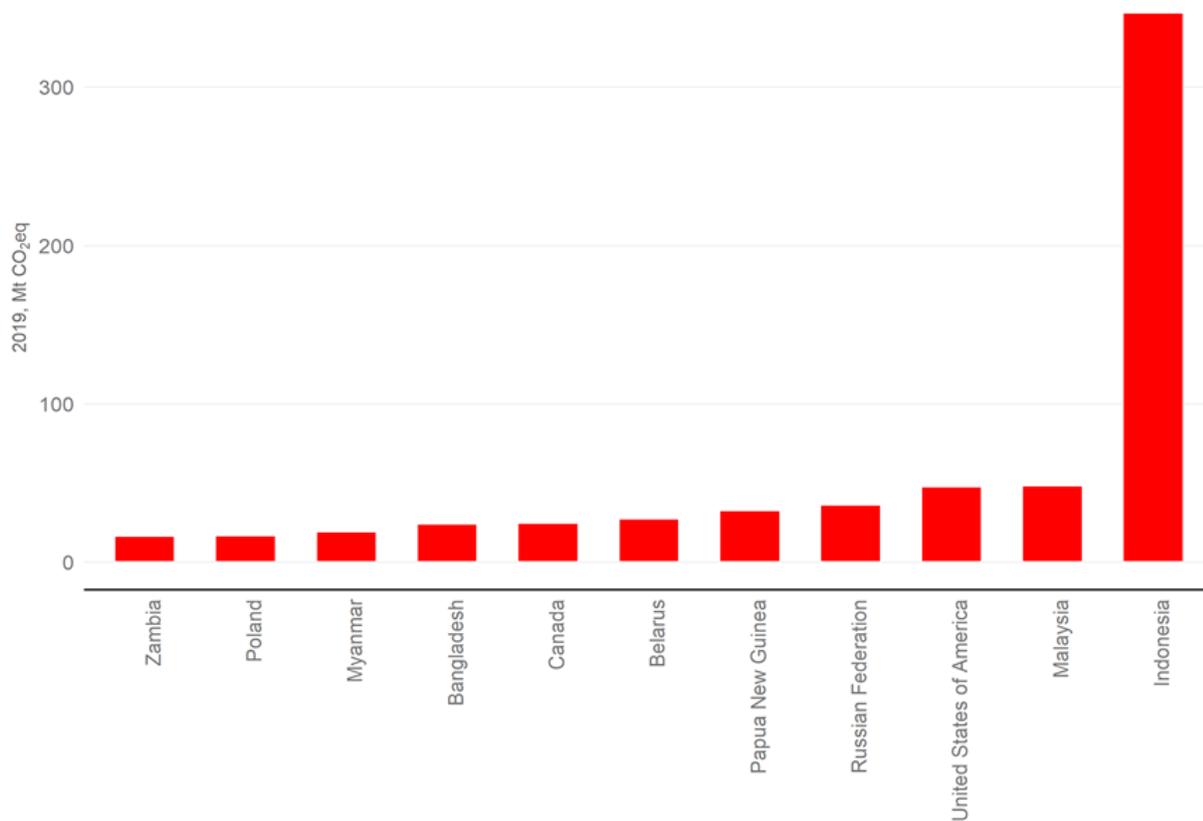
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Figure 7. Top 10 countries by emissions from drained organic soils (75 percent of global emissions)

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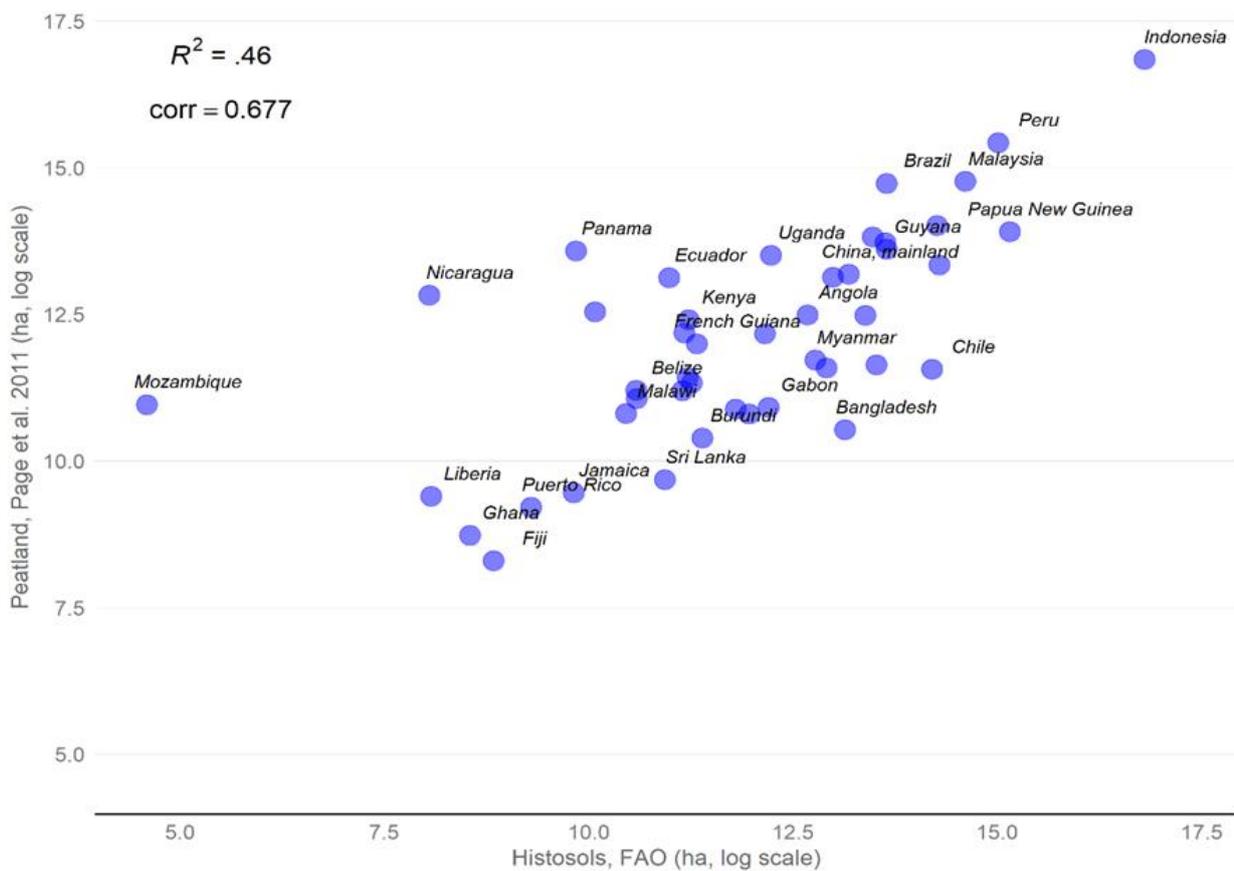
Figure 8. Scatterplot of log-transformed area estimates for organic soils (Page et al., 2011) and FAOSTAT.

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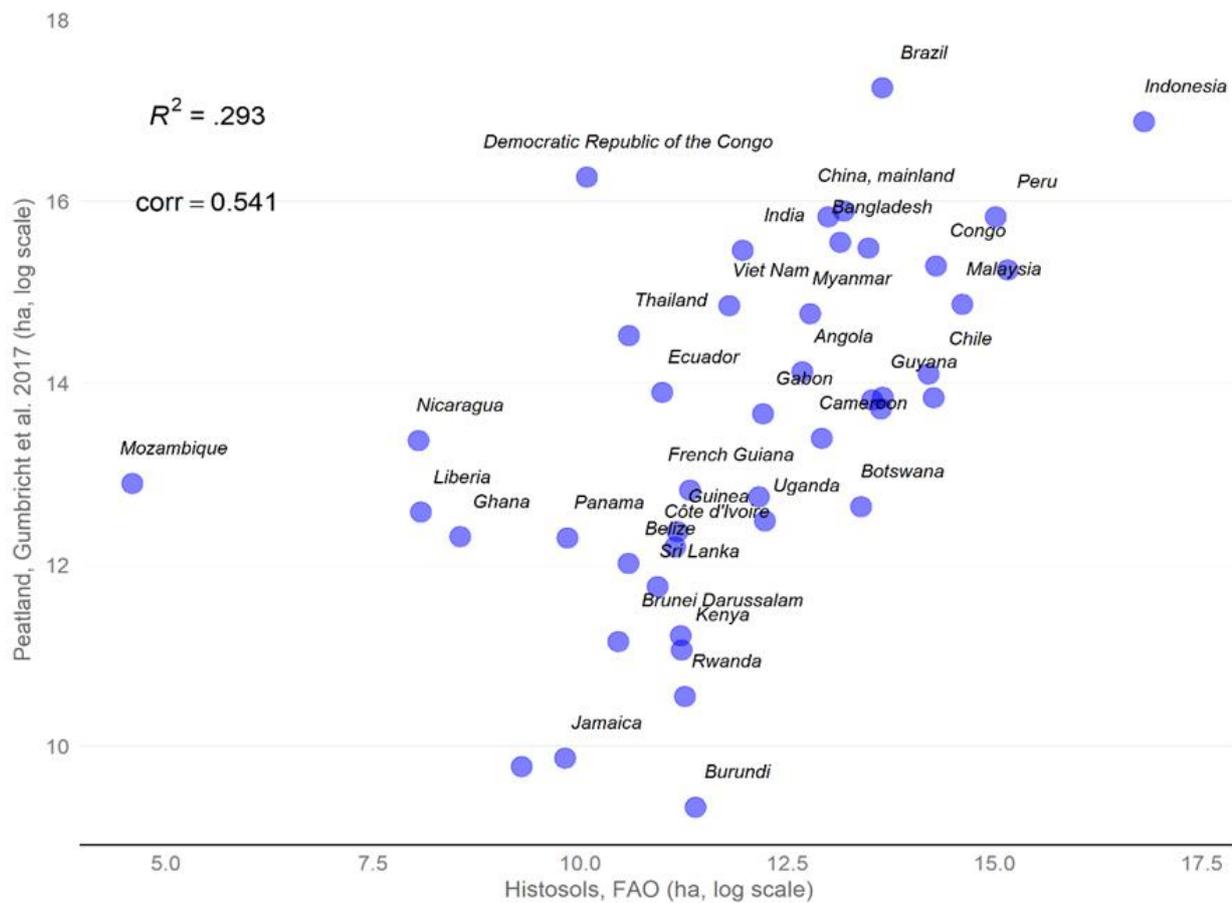
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Figure 9. Scatterplot of area estimates for organic soils in published data (Gumbricht et al., 2017) and FAOSTAT. Data have been log-transformed to avoid dependence on a few large vales.

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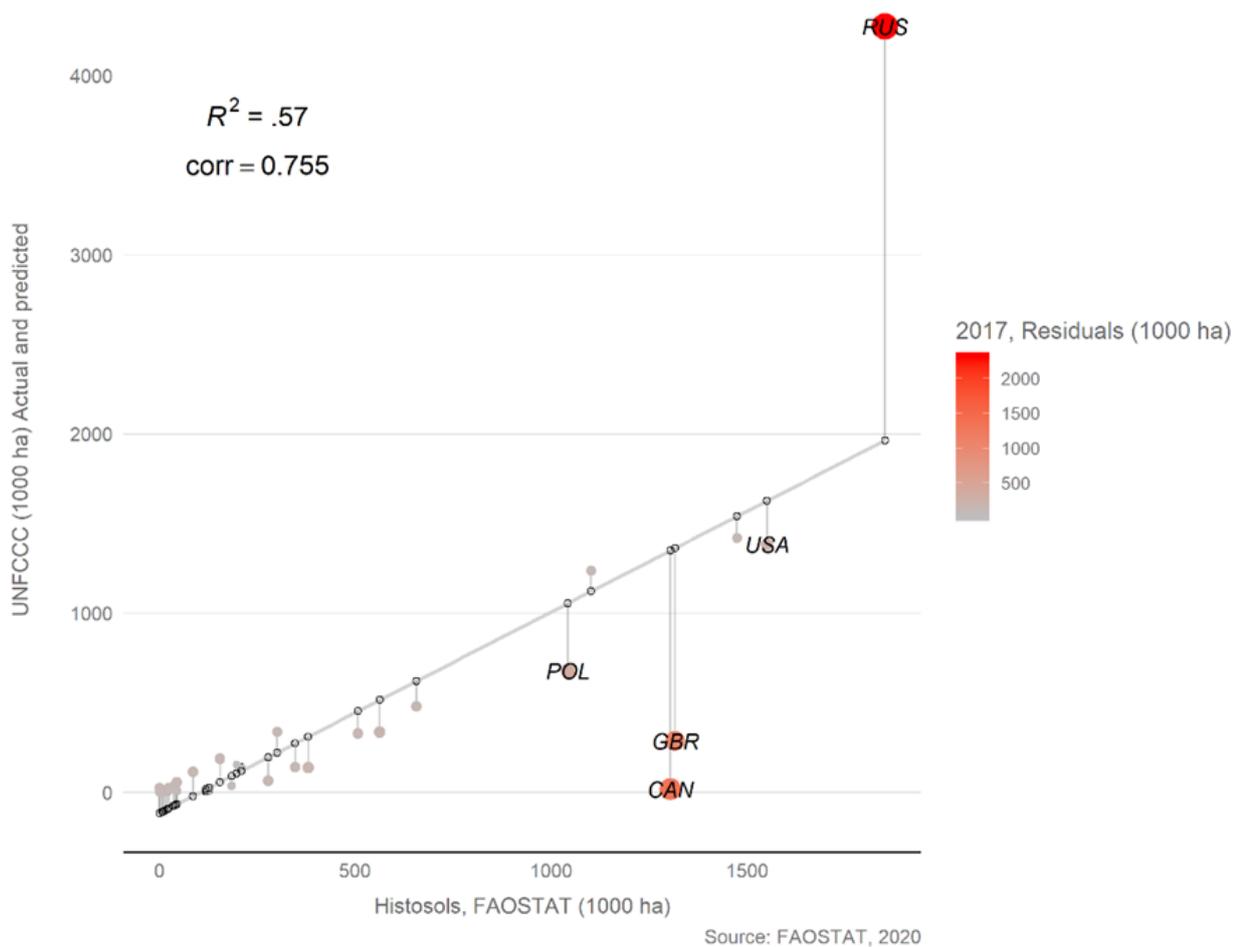
Figure 10. Comparison of FAOSTAT estimates of drained organic soils area *vs* official country data reported to UNFCCC (year 2017). Distance from predicted (on the fitted line) and actual data

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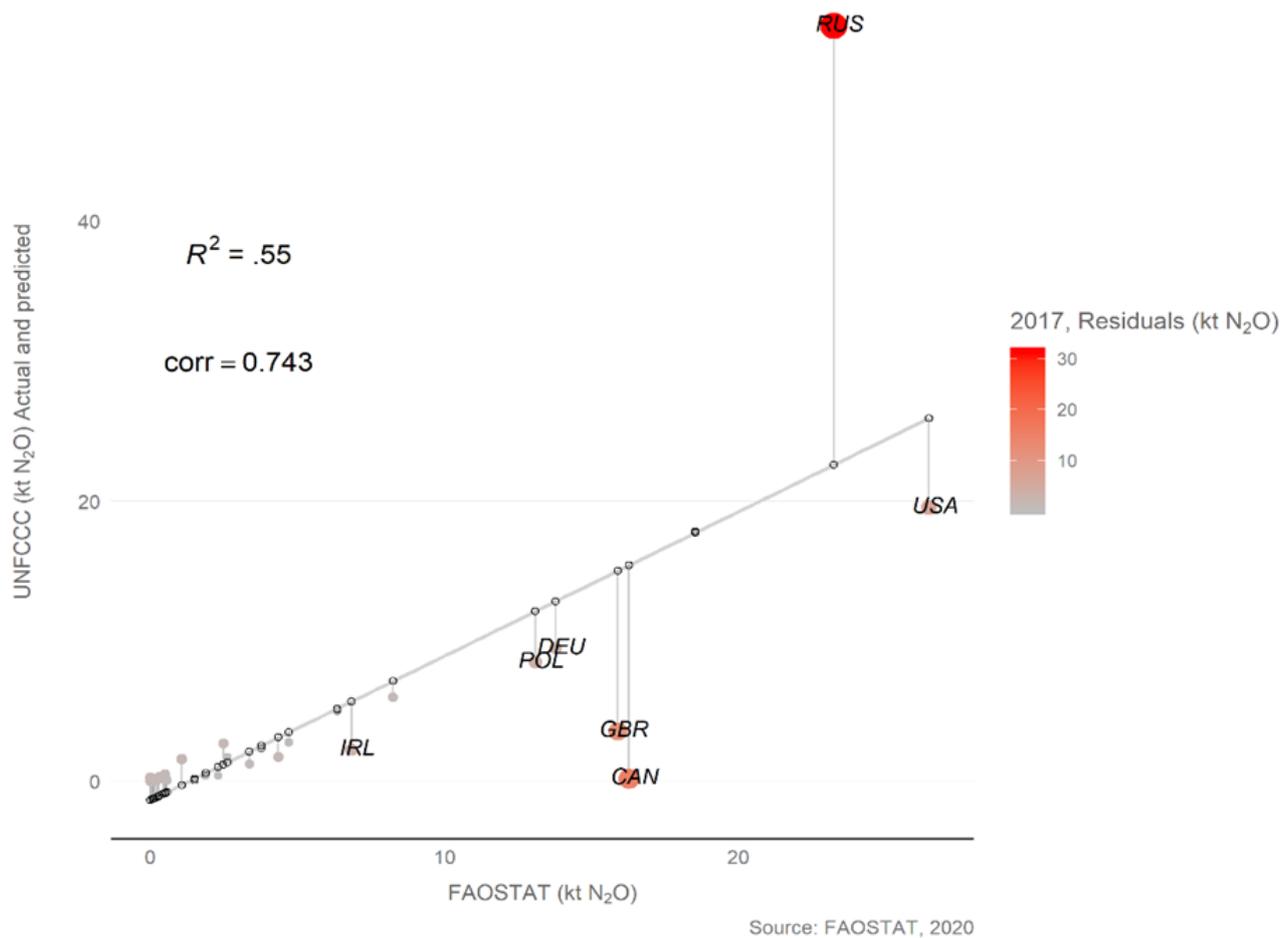
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Figure 11. Comparison of FAOSTAT estimates of GHG emissions (N₂O) compared to UNFCCC data (year 2017)

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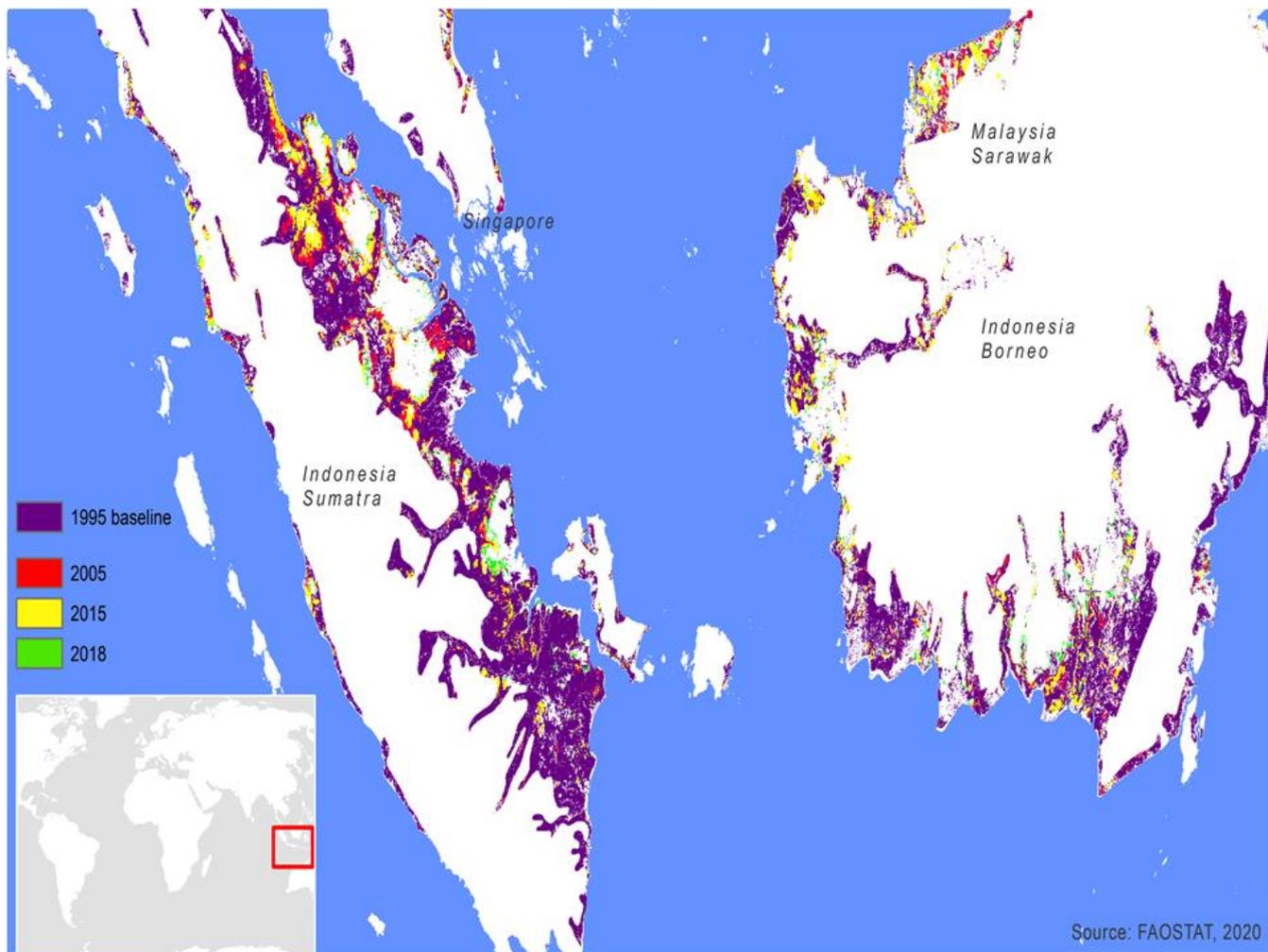
Figure 12. FAOSTAT estimates of the extent of drained organic soils in Indonesia and Malaysia over time, showing total drained area in 1995 and successive additions by 2005, 2015 and 2018

630

635
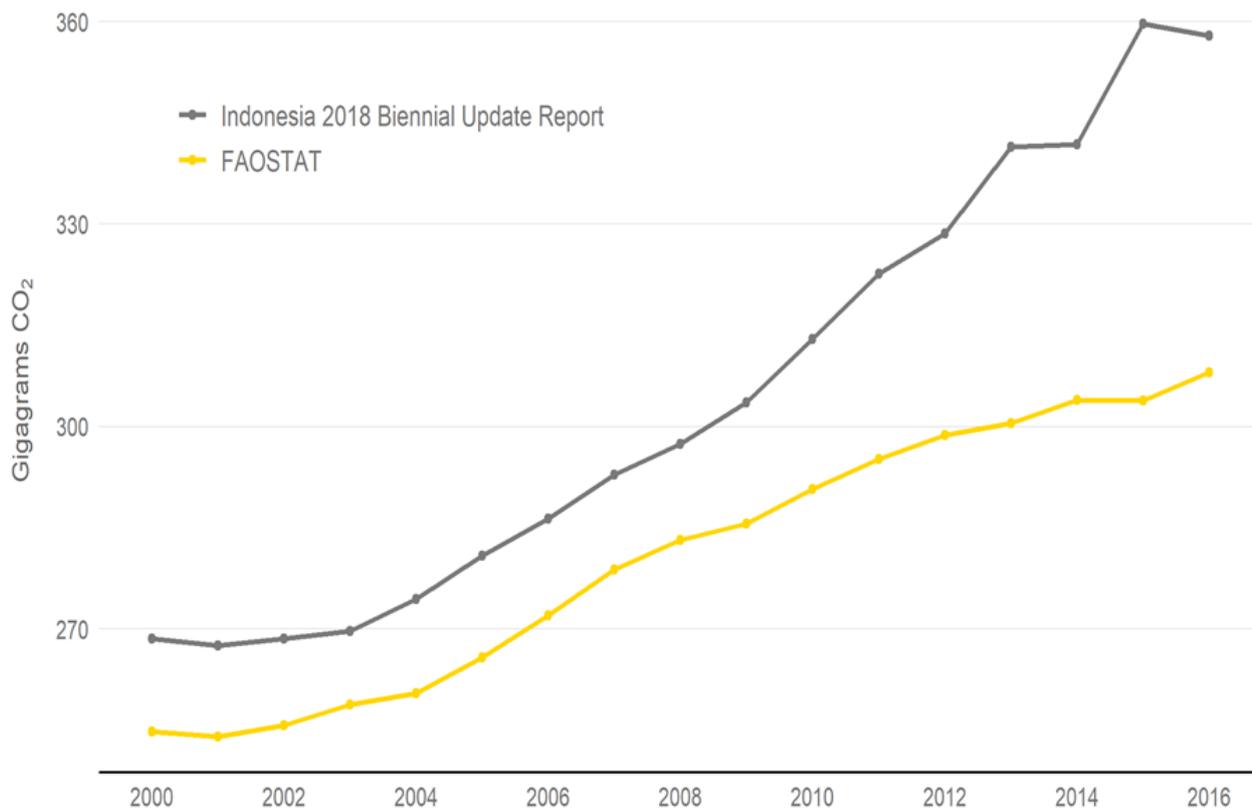
Figure 13. FAOSTAT estimates *vs* reported CO₂ emissions form the drainage of organic soils in Indonesia, 1990–2016

640
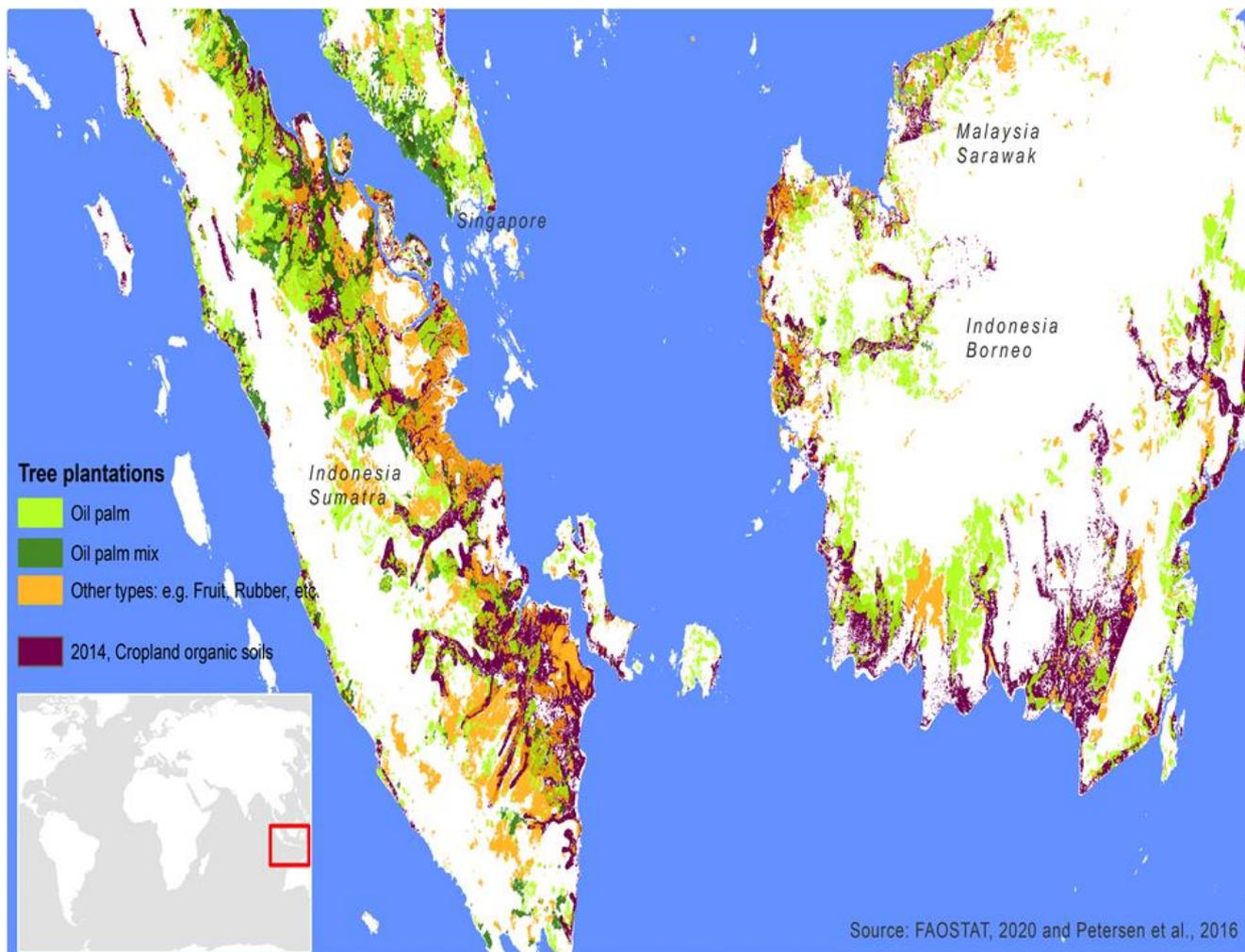
Figure 14. Oil palm and other tree plantations (Petersen et al., 2016) and FAOSTAT Cropland organic soils in 2014

APPENDIX A: Additional results

Table A1. **Original area of** *histosols* **and shares of drained** *histosols* **in 1995[*] and 2019**

Country	Area of histosols (ha)	*of which* drained (%)	
		1995	**2019**
Turkey	16	95.5%	95.5%
Serbia	90	0.0%	92.7%
Guinea-Bissau	101	14.2%	14.2%
Luxembourg	308	0.0%	58.7%
Namibia	853	15.0%	15.0%
Solomon Islands	1,062	1.0%	1.0%
Isle of Man	1,332	80.7%	76.8%
Equatorial Guinea	1,747	0.5%	0.5%
Croatia	2,987	12.6%	11.3%
Nicaragua	3,124	55.7%	39.7%
Liberia	3,208	56.4%	74.8%
Eritrea	3,485	2.3%	2.3%
Slovakia	4,294	58.4%	56.0%
Albania	4,509	85.9%	84.0%
Ghana	5,155	38.7%	33.4%
Central African Republic	5,745	12.2%	17.3%
Fiji	6,867	30.4%	29.5%
Slovenia	7,653	58.7%	83.0%
Montenegro	7,775	0.0%	10.2%
Puerto Rico	10,850	23.4%	15.4%
Republic of Moldova	12,274	52.7%	47.2%
Bosnia and Herzegovina	12,770	36.4%	34.9%
Uruguay	18,213	52.0%	51.2%
Jamaica	18,309	24.7%	34.2%
Panama	18,859	78.5%	78.2%
Costa Rica	21,135	18.5%	14.7%
Belgium	22,985	0.0%	34.3%
Democratic Republic of the Congo	23,750	36.8%	35.7%
Portugal	25,810	50.1%	48.4%
Austria	27,863	41.2%	45.8%
Italy	28,540	81.4%	81.3%
South Africa	31,955	54.3%	63.7%

Malawi	34,745	45.2%	45.2%
Spain	36,030	41.3%	50.7%
Czechia	37,943	29.6%	28.0%
Faroe Islands	38,952	34.6%	34.6%
Belize	39,354	13.3%	14.4%
Thailand	39,548	65.4%	63.0%
Bulgaria	52,362	76.6%	73.8%
Greece	55,569	81.8%	79.8%
Sri Lanka	55,942	57.6%	54.4%
Ecuador	58,961	1.0%	3.3%
Côte d'Ivoire	69,150	55.5%	60.6%
Guinea	71,016	27.0%	26.3%
Brunei Darussalam	73,964	9.0%	7.5%
Kenya	74,610	11.9%	11.9%
Rwanda	77,814	47.7%	46.3%
French Guiana	82,487	0.4%	1.0%
Switzerland	86,097	43.9%	39.9%
Burundi	88,387	77.0%	78.8%
Denmark	111,011	77.5%	76.5%
Democratic People's Republic of Korea	113,916	3.4%	4.1%
Viet Nam	132,725	52.0%	49.9%
India	156,362	67.0%	65.5%
Madagascar	189,666	55.4%	57.6%
Gabon	199,075	4.7%	5.6%
Uganda	204,211	57.1%	56.7%
Nepal	233,847	31.2%	32.8%
Romania	248,517	7.7%	7.7%
New Zealand	254,339	50.2%	49.8%
Hungary	275,678	71.2%	69.0%
Ethiopia	289,128	44.1%	44.9%
France	308,893	70.7%	67.8%
Angola	319,617	2.1%	2.1%
Myanmar	352,812	83.0%	81.8%
Japan	358,961	52.4%	42.9%
Netherlands	395,113	78.4%	75.9%
Cameroon	404,266	6.0%	7.0%
Colombia	437,958	2.8%	4.0%

Australia	440,351	27.0%	27.1%
United Republic of Tanzania	492,667	21.8%	20.6%
Bangladesh	507,083	69.4%	66.9%
China, mainland	530,701	27.5%	28.2%
Botswana	651,384	1.5%	1.7%
Falkland Islands (Malvinas)	667,141	43.3%	43.2%
Iceland	684,893	6.4%	6.4%
Argentina	694,519	29.4%	30.1%
Lithuania	701,767	51.4%	49.4%
Venezuela (Bolivarian Republic of)	710,571	4.0%	5.7%
Latvia	735,751	23.3%	26.9%
Suriname	746,249	1.0%	1.7%
South Sudan	827,363	0.0%	32.9%
Brazil	840,917	1.3%	1.7%
Guyana	844,866	7.4%	9.4%
Estonia	918,164	16.4%	20.1%
Ireland	1,118,046	51.8%	50.3%
Ukraine	1,262,568	55.9%	52.0%
Mongolia	1,311,509	80.6%	81.0%
Chile	1,472,126	3.3%	3.4%
Germany	1,482,858	76.0%	74.4%
Zambia	1,565,696	23.3%	23.2%
Congo	1,609,628	3.3%	3.5%
Poland	1,769,225	61.0%	59.0%
Norway	1,947,518	13.1%	14.4%
Malaysia	2,210,193	20.3%	30.4%
United Kingdom	2,610,052	51.4%	50.4%
Belarus	3,014,298	49.7%	48.9%
Peru	3,300,367	0.0%	0.1%
Papua New Guinea	3,806,847	10.6%	11.5%
Sweden	6,797,032	4.4%	6.0%
Finland	9,205,429	4.5%	5.7%
Indonesia	19,791,043	19.9%	24.4%
United States of America	25,399,312	6.2%	6.1%
Canada	105,758,515	1.2%	1.2%
Russian Federation	116,116,633	1.6%	1.6%

World	**328,935,932**	**7.0%**	**7.5%**

ᵃ 1995 is chosen arbitrarily to account for the reporting of countries after the split of the Soviet Union.

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Table A2. **Global emissions in 1990 and 2019 by gas and by land use**

Land use	Mt by gas		Total in Mt CO_2eq
	N_2O^a	CO_2	
Cropland organic soils	66.4	589.9	656.3
Grassland organic soils	34.9	44.8	79.6
Total emissions in 1990	**101.2**	**634.7**	**735.9**
Cropland organic soils	74.4	675.9	750.3
Grassland organic soils	36.0	46.5	82.5
Total emissions in 2019	**110.5**	**722.4**	**832.9**

655   [a] N_2O emissions converted to CO_2eq through IPCC AR5 GWP (IPCC, 2014b).

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APPENDIX B: Tables for validation

Table B1. **Peat extent from Page et al., 2011, Gumbricht et al., 2017, and FAO area of *histosols*, all in 1000 ha**

		Page et al., 2011	Histosols (FAO)	Gumbricht et al. 2017
		Best estimate from meta-analysis	Spatial layers	
Africa	Angola	264	320	1,359
	Botswana	265	651	308
	Burundi	33	88	11
	Cameroon	108	404	654
	Congo	622	1,610	4,357
	Democratic Republic of the Congo	280	24	11,592
	Gabon	55	199	855
	Ghana	6	5	221
	Guinea	195	71	234
	Côte d'Ivoire	73	69	198
	Kenya	244	75	64
	Liberia	12	3	290
	Madagascar	192	190	343
	Malawi	49	35	70
	Mauritania	6	0	0
	Mauritius	0	0	0
	Mozambique	58	0	398
	Nigeria	184	0	0
	Réunion	0	0	0
	Rwanda	83	78	38
	Senegal	4	0	0
	Sierra Leone	0	0	0
	South Sudan	907	827	906
	Uganda	730	204	263
	Zambia	1,220	1,566	1,021
	Africa *total*	**5,586**	**6,419**	**23,182**
Asia (South East)	Brunei Darussalam	91	74	74
	Indonesia	20,695	19,791	21,342
	Malaysia	2,589	2,210	2,858
	Myanmar	123	353	2,577
	Papua New Guinea	1,099	3,807	4,163

	Philippines	65	0	0
	Thailand	64	40	2,024
	Viet Nam	53	133	2,815
	Asia (South East) *total*	**24,778**	**26,407**	**35,851**
Asia (other)	Bangladesh	38	507	5,667
	China	531	531	8,001
	India	49	156	5,179
	Sri Lanka	16	56	128
	Asia (other) *total*	**634**	**1,250**	**18,974**
Central America & Caribbean	Belize	74	39	165
	Cuba	364	0	0
	El Salvador	9	0	0
	Haiti	119	0	0
	Honduras	453	0	0
	Jamaica	13	18	19
	Mexico	100	0	0
	Nicaragua	371	3	638
	Panama	787	19	218
	Puerto Rico	10	11	18
	Trinidad and Tobago	1	0	0
	Central America & Caribbean *total*	**2,300**	**90**	**1,058**
Pacific	Australia	15[a]	440	2,142
	Fiji	4	7	0
	Pacific *total*	**19**	**447**	**2,142**
South America	Bolivia (Plurinational State of)	51	0	0
	Brazil	2,500	841	30,965
	Chile	105	1,472	1,327
	Colombia	504	438	7,473
	Ecuador	500	59	1,084
	French Guiana	162	82	370
	Guyana	814	845	1,028
	Peru	5,000	3,300	7,499
	Suriname	113	746	998
	Venezuela (Bolivarian Republic of)	1,000	711	5,300
	South America *total*	**10,749**	**8,495**	**56,045**
Total		**44,066**	**43,108**	**137,252**

[a] In Page et al., 2011, Australia estimates limited to Australia, Queensland.

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Table B2. FAOSTAT estimates and UNFCCC reported country data: area drained and N$_2$O (kt) emissions, by country in Annex I group[a], 2017

ISO3	Country	UNFCCC	FAOSTAT	UNFCCC	FAOSTAT
		Area drained (ha)		N$_2$O emissions (kt)	
AUS	Australia	4,000	119,195	0.05	1.51
AUT	Austria	12,954	12,763	0.17	0.16
BEL	Belgium	2,520	7,899	0.03	0.10
BGR	Bulgaria	41,267	38,750	0.52	0.49
BLR	Belarus	1,419,100	1,474,262	17.84	18.53
CAN	Canada	16,156	1,304,454	0.20	16.27
CHE	Switzerland	17,339	34,369	0.22	0.43
CZE	Czechia	--	10,593	--	0.13
DEU	Germany	1,235,057	1,102,052	9.52	13.77
DNK	Denmark	112,792	84,980	1.60	1.06
ESP	Spain	--	18,342	--	0.23
EST	Estonia	34,815	183,505	0.44	2.30
FIN	Finland	327,616	506,840	5.03	6.34
FRA	France	139,056	209,149	1.75	2.62
GBR	United Kingdom	285,700	1,316,388	3.6	15.9
GRC	Greece	6,665	44,520	0.08	0.56
HRV	Croatia	2,685	336	0.03	0.00
HUN	Hungary	--	190,462	--	2.39
IRL	Ireland	333,853	562,872	2.26	6.83
ISL	Iceland	55,598	43,859	0.08	0.51
ITA	Italy	25,480	23,247	0.32	0.29
JPN	Japan	185,592	154,160	0.39	1.89
LTU	Lithuania	138,758	346,350	1.74	4.35
LUX	Luxembourg	--	181	--	0.00
LVA	Latvia	152,160	197,363	2.71	2.48
NLD	Netherlands	337,102	300,076	2.36	3.77
NOR	Norway	63,862	277,520	1.26	3.36
NZL	New Zealand	8,020	126,770	0.10	1.51
POL	Poland	678,000	1,042,266	8.52	13.08
PRT	Portugal	--	12,598	--	0.15

ROU	Romania	6,387	19,234	0.08	0.24
RUS	Russian Federation	4,274,300	1,852,512	53.93	23.24
SVK	Slovakia	--	2,399	--	0.03
SVN	Slovenia	2,501	6,361	0.03	0.08
SWE	Sweden	136,692	379,122	2.79	4.71
TUR	Turkey	21,840	15	0.27	0.00
UKR	Ukraine	478,400	656,586	6.01	8.25
USA	United States of America	1,383,162	1,551,534	19.56	26.48
Total		**11,939,429**	**14,213,882**	**144**	**184**

665 [a] Data for this reporting category are not occurring (NO) in the UNFCCC tables for Cyprus, Czechia, Hungary, Kazakhstan, Luxembourg, Malta, Monaco, Portugal and Spain. Data were not estimated in Slovakia (NE).