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 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 (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 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

Organic soils are, generally speaking, wet soil 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 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 available organic substrate. Agriculture is a major cause of drainage of organic soils around the world, especially after the 90s due to the cultivation of permanent crops such as oil palm in south-east Asia. 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, 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, 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

Organic soils are characterized by high concentrations of organic matter. They mostly develop under poorly drained, wet conditions and are found at all altitudes, with the vast majority occurring in lowlands (Gorham, 1991; 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) described *histosols* as soils that develop in (predominantly) “moss peat in boreal, arctic and subarctic regions, *via* moss peat, 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. It should be noted that these might include areas that are not strictly defined as peat soils. 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. Peat emissions are unique as 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 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):

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

where:

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

$\Sigma_{y,j} A$ = 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 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 (FAO and IIASA, 2012) annual maps of land cover (ESA CCI, 2020); a combined livestock density map (Robinson et al., 2014); and a map of climatic zones (JRC, 2010). Details on these inputs are given in following sections. The area drained for cropland and grassland organic soils represent the time-dependent components of Eq. (1). They were calculated as follows:

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

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

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”, derived from land cover classes (cropland or grassland) in global land cover maps (C3S, 2019) 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 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 the drainage for agriculture. Drainage stimulates the oxidation of organic matter previously built up under a largely anoxic 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 computations by pixel 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 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 derived by pixel the area of organic soils that is drained for agricultural activities. In order to support cultivation, organic soils need to be drained. Heavy grazing on grassland organic soils might result in N and C losses and overall degradation (Worrall and Clay, 2012; Martin et al., 2013; Noble et al., 2018). The following sections provide more details about the information necessary to implement the computations above.

2.1 Soils

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) (FAO and IIASA, 2012). 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 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). Soil units in the HSWD dataset dominated by histosols are characterized by soils with a thick layer of strongly decomposed acidic organic material, 70 cm thick, with continuous rock at 80 cm and that develop in environments with a large excess of precipitation.

2.2 Land cover and land use

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 Space 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). Since 2016, CCI LC maps became part of the European

Copernicus Climate Change Service which released at the end of 2019 (C3S, 2019), three additional global land cover (LC) products 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 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). To cover the 1990–2019 period of the final FAOSTAT dataset, the 1992 land cover values are carried backwards to 1990. Land cover data for 2019 are carry-forwards of the latest available year (2018).

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). Namely, we used version 2.1 of the GLW maps, with 1 km resolution and 2010 as reference year. Animal numbers by pixel were first converted in livestock units (LSU) (FAO, 2011), and pixels with values higher than 0.1 (Critchley et al., 2008; Worrall and Clay, 2012) were selected for use in Eq. (3). As this methodology focuses on agricultural land uses it does not investigate the impacts of wildlife on the organic soils.

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 (JRC, 2010). 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 (Fig. 4).

Default IPCC emissions factors 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 (Fig. 5). As one country may encompass more than one climatic zone, when emissions are aggregated at national level in FAOSTAT, 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 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 United Nations Framework Convention on Climate Change (UNFCCC) 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 is available through the new FAO Map Catalog and Geospatial Platform (FAO, 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 Assessment Report (IPCC, 2007); and *c)* IPCC Fifth Assessment Report (IPCC, 2014b) (Table 4). All data are also available at Zenodo as open access (Tubiello and Conchedda, 2020) with DOI 10.5281/zenodo.3942370. They can be downloaded at https://zenodo.org/record/3942370#.XxWJjygzbIU.

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 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, global GHG emissions from drained cropland and grassland organic soils were 833 Mt CO_2eq, calculated applying AR5 GWP for the N_2O emissions (IPCC, 2014b). They were 13 percent and 10 percent higher when compared to 1990 and 2000 respectively, representing 8 percent of total agriculture and related land use emissions (Fig. 6). In 2019, CO_2 and N_2O contributed 87 percent and 13 percent of global emissions. Grassland organic soils were responsible for about 10 percent of these emissions while the vast majority was due to the drainage for cropping. These relative contributions have changed little since 1990 (Appendix A, Table A1).

In 2019, among countries where the area of *histosols* is above 1Mha (see Appendix A, Table A2), the larger proportions of drained organic soils 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, respectively). In 2019, three-fourths of the global emissions from organic soils were from only 11 countries (Fig. 7), Malaysia and Indonesia together were responsible for nearly half (47 percent) of total emissions.

4 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) and may be extended to this revision. Importantly, while this methodology focuses on the impact of drainage on agricultural organic soils, it should be acknowledged that peat degradation may occur under other land uses such as in forest soils. We presented in earlier papers our work on peat fires and their role on global GHG emissions (Rossi et al., 2016; Prosperi et al., 2020) and disseminate the associate statistics in FAOSTAT (FAO, 2020f). This component is however not part of the present discussion.

The methodology developed herein may result in some cases in reduction in the drained area of organic soils during the 30 years of the analysis (see Appendix A, Table A2). In such cases, the pixel-level proportions that are applied to identify the cropland and grassland cover, have thus detected corresponding changes in land cover. The lack of information on rewetting and the scale of this analysis prevent however to understand whether these changes actually happened in the area of organic soils as result of rewetting of the drained peats or are instead an artefact of the spatial methods.

The IPCC introduced with the 2013 Wetlands Supplement additional methodological guidance on inland drained organic soils (IPCC, 2014a), with a specific focus on the rewetting and restoration of peatland that was not included in the 2006 Guidelines. Limited country-specific activity data on rewetting prevented however implementing the Supplement refined methods in this methodology.

We estimated that by applying the revised EFs for C and N_2O (Table 5) from the Supplement on Wetlands (IPCC, 2014a) to our methodology, the global emissions from agricultural drained organic soils in 2019 would be 883 Mt CO_2eq, thus about 6 percent more than estimated using the EFs from the 2006 Guidelines (see Appendix A, Table A3). This figure would be the result *ceteris paribus* of the downward revision of both C and N_2O EFs for cropland organic soils in the tropics combined with the large upward revision of grasslands C and N_2O EFs in the boreal and temperate zones. In addition, C emissions from grassland organic soils in the tropics would increase about twofold with the revised EFs whereas N_2O emissions would decrease threefold. Thanks to the new scientific evidence, the uncertainty of the EFs in the Supplement on Wetlands are overall smaller than in the 2006 Guidelines (Table 5) but remain very large (47–186 percent) for the main component of emissions—the C emissions from cropland organic soils in the tropics. With the only exception of the estimates for grassland organic soils in boreal and temperate zones, our estimates are well within the range of the uncertainties if the revised EFs from the Supplement were applied to our methodology. It should be noted that the Supplement on Wetlands (IPCC, 2014a) also includes new guidance to estimate the amount of dissolved organic carbon (DOC) that is carried out on ditches in drained peatlands which was not part of the 2006 Guidelines (IPCC, 2006). This was however not part of this comparison.

The Tier 1 methods applied in this study do not differentiate between long-term drained organic soils and soils after initial drainage when carbon losses are the highest (Hooijer et al., 2012; IPCC, 2014a). It should be also noted that the progressive soil mineralization associated with prolonged drainage may lead eventually to peat depletion, particularly in shallow soils (Humpenöder et al., 2020). This in turn, might affect the scale of emissions thus adding uncertainty to our current estimates. Country-specific information on the thickness of the organic layer and the depth and length of drainage is however currently missing to assess the extent of peat depletion worldwide.

5 Data Validation

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.

5.1 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 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 kilometres (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 6). In addition, while acknowledging the large differences existing between published estimates by regions, FAOSTAT estimates remained consistently within the observed ranges. More specifically, FAOSTAT estimate of the 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, 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 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. These authors define peat as any soil having at least 30 cm of decomposed or semi-decomposed organic material with at least 50 percent of organic matter. 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 Mkm^2 , which compared well with the value of 0.44 Mkm^2 of Page, but both estimates are about a third of the total reported in Gumbricht et al. (2017) (1.37 Mkm^2). The following factors may contribute to explain the discrepancy observed with Page et al. (2011). Firstly, the expert model of Gumbricht et al. (2017) does not account for soil lithology and composition other than through soil wetness responses and the assessment of the hydrological conditions suitable to peat storage measured primarily through elevation data, soil moisture (phenology) and climate. Secondly, while Gumbricht et al. (2017) report that mangroves are considered to meet the criteria of depth and organic matter content needed for peat definition, these authors acknowledge that mineral soils may prevail in mangroves and that additional ground-truthing is needed to validate if mangroves contain peat as defined in their expert system.

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 from 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 contributors in south-east 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 explain only partially the variability in the peat area as mapped by these authors. ($R^2=.293$) (Fig. 9). For a 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 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), consistent with recent studies (Dargie et al., 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 peatland exists. To this end, ongoing international efforts such as the Global Peatlands Initiative (2020) are expected to improve and consolidate current knowledge.

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

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 UNFCCC for validation of these FAOSTAT estimates. We looked both at data from the 2019 National Greenhouse Gas Inventories (2017 as last available year in the data) of the Annex I Parties and to the most recent (2018) national communication from Indonesia, a top emitter country.

5.2.1 Annex I parties

UNFCCC data were available for thirty-eight countries belonging to the Annex I parties to the climate Convention (2019 inventories, 2017 last reported year). 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 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, 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 soil 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 IPCC sector Agriculture. C fluxes from the drainage of organic soils are instead reported by Annex I countries under Land Use, Land Use Change, and Forestry (LULUCF). 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

(Barthelmes et al., 2015). Beside the differences in activity data (area drained) that were observed earlier, differences may also be due to countries applying higher Tiers than the default methodology we applied in FAOSTAT as well as to the definition of land uses causing drainage.

FAOSTAT N_2O 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 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 Canada (16 *vs* 0.2 kt N_2O). In this latter country, the discrepancy was due to FAOSTAT estimating three times a larger extent of drained agricultural soils than reported by Canada in the 2019 inventory and report to the Climate Convention (2019, Canada National Inventory Report 1990–2017, Part 2).

FAOSTAT results are in line with other independent assessments, for instance a study for countries in the Baltic region (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) developed for Germany a spatially representative Tier 2 approach for organic soils using detailed activity data and national 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 difference, which was mostly due to the different applied EFs, suggests that even FAOSTAT estimates may not fully grasp the potential for mitigation from the rewetting of drained organic soils.

5.2.2 Non-Annex I parties

Over forty 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, 2020g) (Fig. 12).

We compared FAOSTAT estimates of GHG emissions from the drainage of organic soils in Indonesia to those reported by the country for the period 2000–2016 in the second Biennial Update Report (BUR) to the Climate Convention (submission on December 2018). Data reported from Malaysia do not allow instead for a similar comparison. National reported data from Indonesia 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 data. The average FAOSTAT GHG emissions over 1990–2016 were 281 Mt CO_2eq *vs* 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. A possible reason for the observed discrepancy is that the national communication applies three distinct EFs for oil palm, rubber and other annual crops. Additionally, while FAOSTAT estimates only include the drainage and emissions from agricultural uses, Indonesia also reports the emissions from peat decomposition under forest land use. The distance between national data and our results is however well within the combined uncertainty (53 percent) for activity data and EFs as reported in the Indonesia BUR. 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).

5.2.3 Emissions factors for palm oil plantations

The establishment of new oil palm plantations is recognized as a main driver for the drainage of tropical peatlands in Indonesia and Malaysia (Hooijer et., 2010; Hooijer et al., 2012; Miettinen et al., 2012; Dohong et al., 2018; Cooper et al., 2020; FAO, 2020g). As a supplementary validation of Eq. (1)–(2), we combined spatially our layer of cropland organic soils to an additional map of tree plantations produced by Petersen et al. (2016) (Fig. 14). These authors mapped the distribution of different types of plantations—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. The types of mapped plantations are oil palm and oil palm mix; rubber and rubber mix; wood fibre / timber and other mixed types. This additional analysis allows to compare FAOSTAT results to those from peer-reviewed literature, with a focus on emissions factors from oil palm plantations (*i.e.* the emissions per unit area of oil palm on drained organic soils).

In 2014, FAOSTAT crop statistics (FAO, 2020h) on oil palm harvested area reported a total of 8.1 Mha in Indonesia and 4.7 Mha in Malaysia. Petersen and associates generated estimates that were consistent with FAOSTAT data. They mapped the 2014 cover of oil palm plantations to be 11.7 Mha and 5.3 Mha, in Indonesia and Malaysia respectively. Of these, based on our combined analysis of the plantations map and of the cropland organic soils, about 9 percent in Indonesia and 4 percent in Malaysia were organic soils drained for establishing tree plantations (Table 7). In Indonesia, the oil palm plantations mapped by Petersen and colleagues were responsible for about one third of the 2014 emissions from all cropland organic soils in the country. In Malaysia, the relative contribution of oil palm plantations was even larger and about half the total emissions from cropland organic soils (Table 8).

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. Available literature is largely based on in situ measurements which typically analyse 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. When more than one EF was reported in the selected studies, we extracted for this comparison the EFs from mature oil palm plantations (5 or more years after initial drainage), considering these more directly comparable to our methods (Table 8). Values from the selected literature 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 a 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.

6 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 disaggregated by gas (N_2O and CO_2) and land use class, cropland and grassland. Results are disseminated in three separate FAOSTAT domains. These FAOSTAT statistics represent the only available global dataset in the world today showing country, regional and global time series on drained organic soils. The underlying spatial data are also publicly available.

In 2019, FAOSTAT estimated that nearly 25 million ha of organic soils were drained from agriculture and were responsible for 833 Mt 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-east 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 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 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 to 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.

Author contributions

FNT and GC devised the methodology and GC processed the data and produced the graphics. Both authors analysed the data and drafted the manuscript. GC revised and edited the final document.

Competing interests

The authors declare that they have no conflict of interest.
The views expressed in this publication are those of the authors and do not necessarily reflect the views or policies of FAO.

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APPENDIX A: Additional results

Table A1. **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**

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

Table A2**. 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.

Table A3**. Comparison of our emissions estimates by land use and gas generated applying the EFs from the 2006 Guidelines (IPCC, 2006) with emissions estimates if *ceteris paribus* the EFs from the Wetlands Supplement (IPCC, 2014a) were applied instead to the methodology**

	FAOSTAT emissions with EFs from IPCC 2006 Mt CO_2eq			**Simulated emissions estimates if applying EFs from IPCC 2014 Mt CO_2eq**		
	C	**N_2O**	**Total**	**C**	**N_2O**	**Total**
Cropland organic soils						
Boreal* – *Temperate	202.8[a]	22.3[a]	225.1	240.3	36.3	276.6 *(219.9–336.0)*
Tropics	473.1	52.1	525.2	331.2	16.3	347.5 *(163.1–591.4)*
	675.9	74.4	**750.3**	571.5	52.6	**624.0 *(383.0–927.4)***
Grassland organic soils						
Boreal* – *Temperate	14.0[a]	10.8[a]	24.8	176.2	12.0	188.1 *(125.1–371.3)*
Tropics	32.6	25.2	57.8	62.5	7.9	70.4 *(33.0–122.8)*
	46.5	36.0	**82.5**	238.7	19.8	**258.6 *(158.2–494.1)***
All agriculture-drained organic soils						
	722.4	110.5	**832.9**	624.0	258.6	**882.6 *(541.2–1421.5)***

[a] Estimates are made averaging the EFs for Boreal and Cool Temperate and EFs for the Temperate zones as reported in the 2006 Guidelines (IPCC, 2006).

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.

Table B2. **FAOSTAT estimates and UNFCCC reported country data: area drained and N_2O (kt) emissions, by country in Annex I group[a], 2017**

ISO3	Country	UNFCCC	FAOSTAT	UNFCCC	FAOSTAT
		Area drained (ha)		*N_2O 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**

[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).

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Tables

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	
11[a]	*Cropland, rainfed, herbaceous cover*	85%
12[a]	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.

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.

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_2O-N (kg ha^{-1} yr^{-1})**		***Uncertainty***
	Cropland	**Grassland**		**Cropland**	**Grassland**	
1. Warm Temperate Moist	10	2.5	± *90%*	*8*		*Range 2 – 24*
2. Warm Temperate Dry						
3. Cool Temperate Moist	5	0.25		8[b]		
4. Cool Temperate Dry						
5. Polar Moist						
6. Polar Dry						
7. Boreal Moist						
8. Boreal Dry						
9. Tropical Montane	20	5.0		16		*Range 5 – 48*
10. Tropical Wet						
11. Tropical Moist						
12. Tropical Dry						

[a] Adapted from Table 5.6, Table 6.3 (for CO_2) and Table 11.1 (for N_2O) of IPCC (2006). [b] Default value not included in IPCC (2006), assumed equal to EF values for Cool Temperate zones.

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_2O	310	298	265

Table 5. **Emissions/Removal factors (EFs) for inland drained organic soils by land use and gas, in the 2013 Wetlands Supplement (IPCC, 2014) and percentage variations from the corresponding EFs in the IPCC 2006 Guidelines**

	EF tonnes CO_2-C $ha^{-1}yr^{-1}$	95% CI	Change (%) from EF in 2006 Guidelines	EF kg N_2O-N $ha^{-1}yr^{-1}$	95% CI	Change (%) from EF in 2006 Guidelines
Cropland organic soils						
Boreal / Cool Temperate	**7.9**	6.5—9.4	+58%	**13**	8.2—18	+63%
Warm Temperate	**7.9**	6.5—9.4	-21%	**13**	8.2—18	+63%
Tropical	**14.0**[a]	6.6—26	-30%	**5**	2.3—7.7	-69%
Grassland organic soils						
Boreal / Cool Temperate	**5.7**	2.9—8.6	+2180%	**9.5**	4.6—14	+19%
Warm Temperate	**6.1**	5.1—7.3	+144%	**8.2**	4.9—11	+2%
Tropical	**9.6**	4.5—17	+92%	**5**	2.3—7.7	-69%

[a] Corresponding to category Cropland and fallow, drained. This was reported as general EF in the absence of additional information on cropland type.

Table 6. **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 et al., 2018 and FAO estimates for Europe include the Russian Federation.

Table 7. **Area of oil palm and other tree plantations (mapped from Petersen et al., 2016), their distribution in cropland organic soils and corresponding emissions, Indonesia and Malaysia in 2014. Share of total emissions by type of plantation from the country cropland organic soils is also shown. In 2014, total emissions from cropland organic soils were 318 Mt CO_2eq in Indonesia and 45 Mt CO_2eq in Malaysia**

	Area Mha (Petersen et al., 2016)	***of which* in cropland organic soils (*ibidem*)**	**Mt CO_2**	**Mt N_2O**	**Mt CO_2eq**	**Share (%) of total emissions from country crop organic soils, by plantation type**
			Indonesia			
Oil palm	11.7	0.9	66.8	$23*10^{-3}$	72.8	23%
Oil palm mixed	2.4	0.3	10.1	$3*10^{-3}$	19.5	6%
Other tree plantations (rubber, fruits, fibre / wood)	8.7	0.8	58.2	$20*10^{-3}$	63.5	20%
All tree plantations	**22.8**	**2.0**	**76.9**	**$26*10^{-3}$**	**155.9**	**49%**
			Malaysia			
Oil palm	5.3	0.2	16.3	$6*10^{-3}$	17.8	38%
Oil palm mixed	1.9	0.1	3.8	$1*10^{-3}$	4.1	9%
Other tree plantations (rubber, fruits, fibre / wood)	1.4	0.1	4.2	$1*10^{-3}$	4.6	10%
All tree plantations	**8.6**	**0.3**	**24.3**	**$8*10^{-3}$**	**26.4**	**57%**

Table 8**. Comparison of EFs for oil palm plantations on organic soils from peer-reviewed literature and combined FAOSTAT / Petersen et al. (2016) spatial analysis**

Source	**CO_2eq ha^{-1} yr^{-1}**
Published studies	
Page et al., 2011	86–100
Hooijer et al., 2012[a]	78
Agus et al., 2013[b]	43
Couwenberg and Hooijer, 2013 [b]	66
Hashim et al. 2018	13–53
Matysek et al., 2018	86–117
Cooper et al., 2020 [c]	97
FAOSTAT / Petersen et al., 2016	78

[a] Value 18 years after drainage. [b] Value more than 5 years after drainage. [c] Value for mature oil palm plantations (over a 30-year cycle).

Figures

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

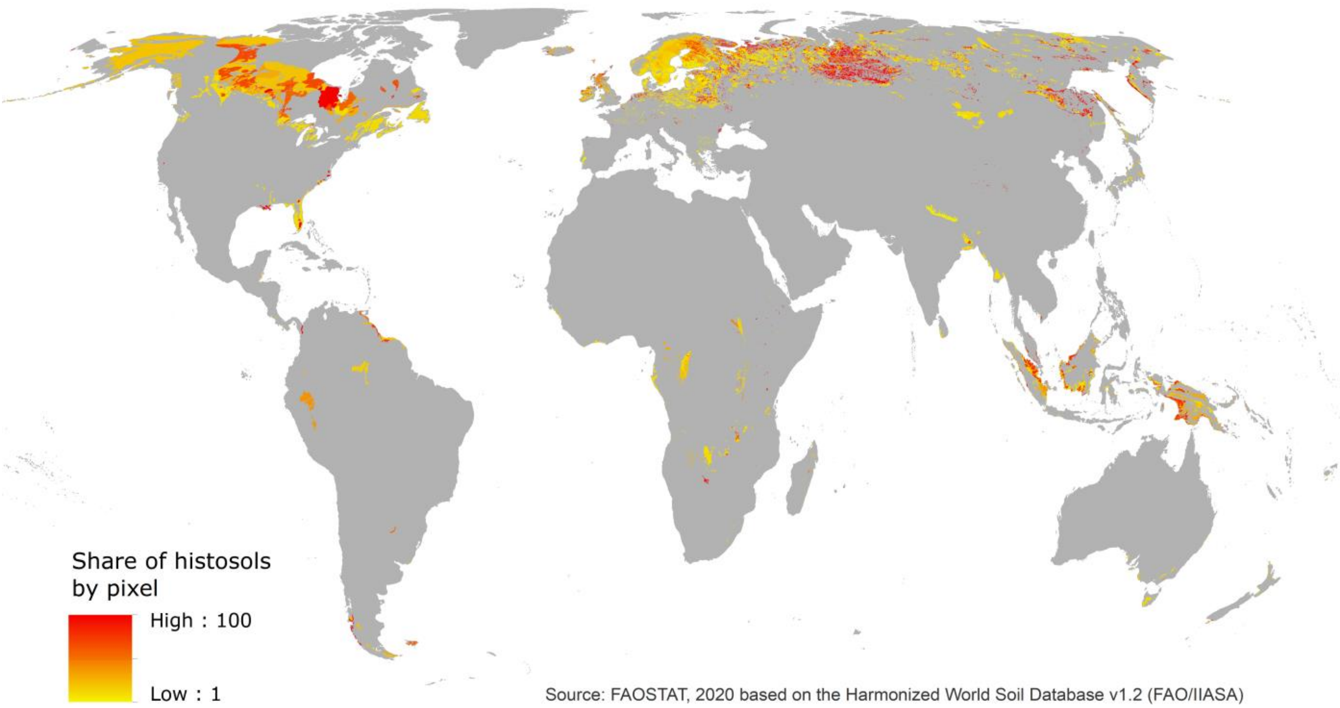
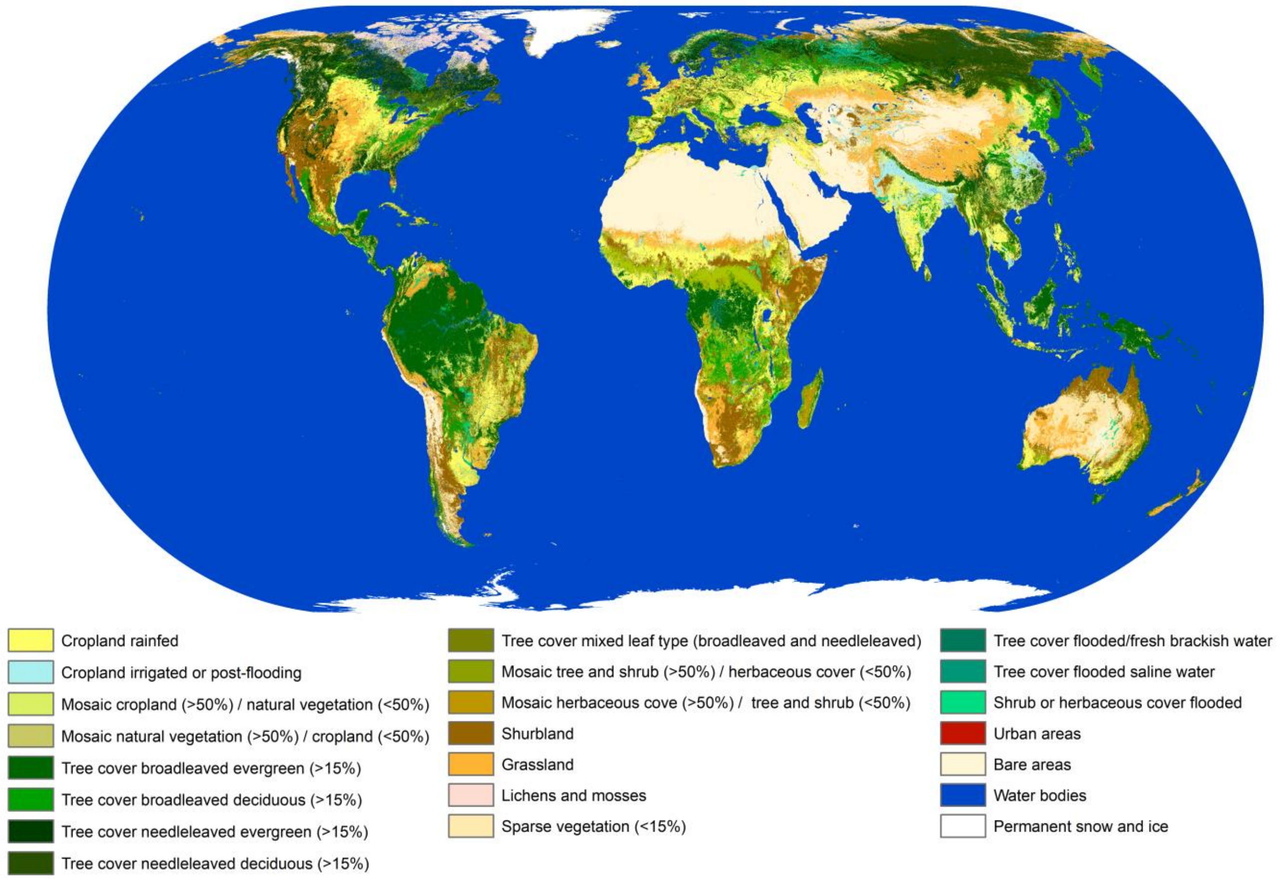


Figure 2. Global land cover, 1992–2018 composite information from CCI-LC maps (ESA CCI, 2020)



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

Figure 3. Global distributions of cattle, sheep and goats, Gridded Livestock of the World (Robinson et al., 2014)

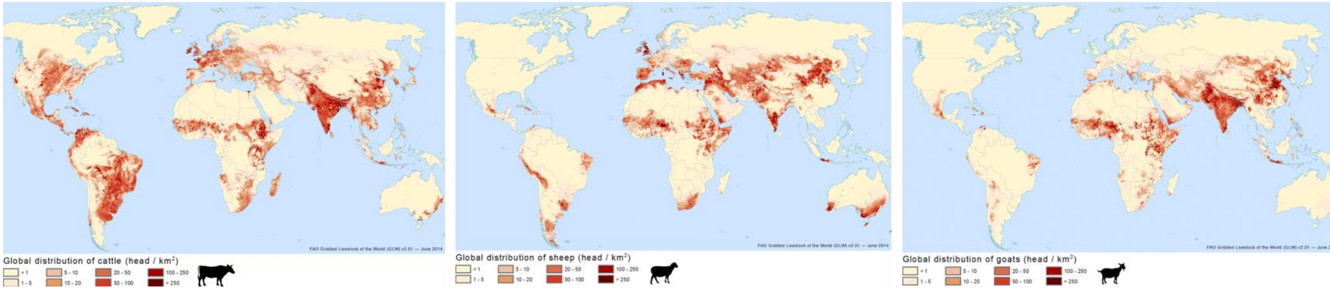
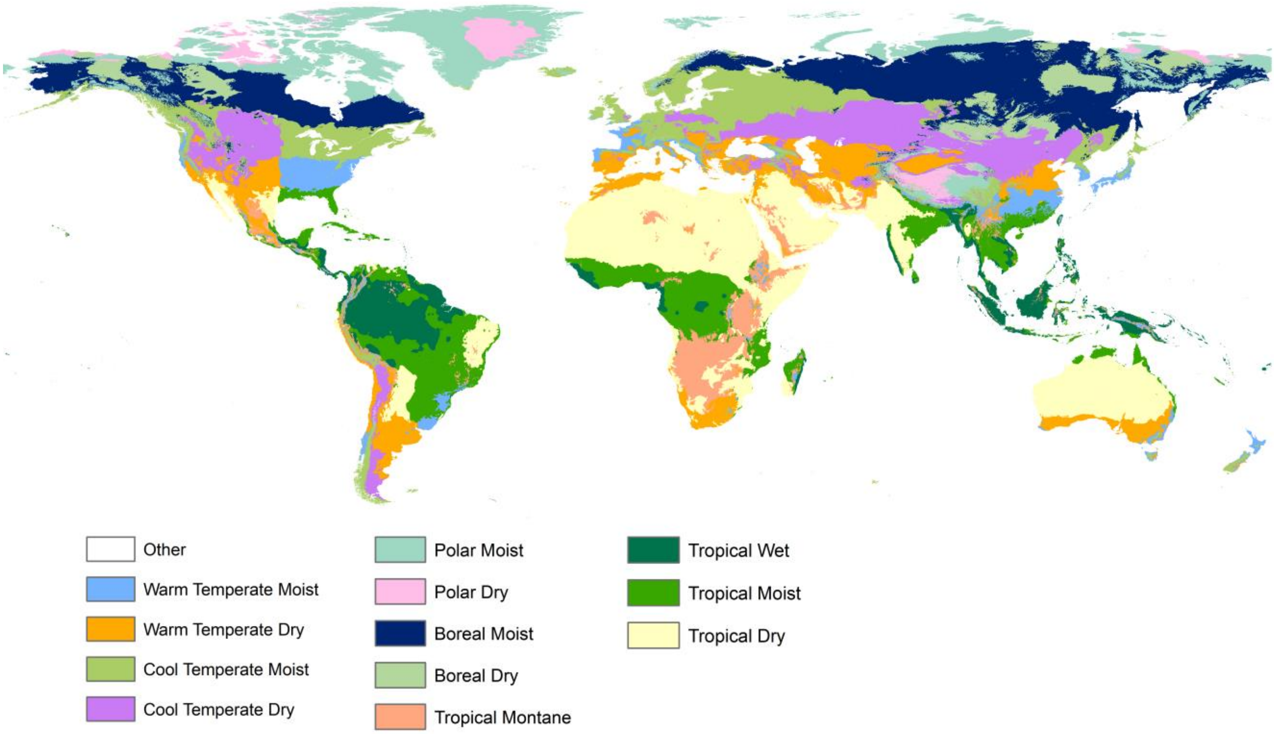
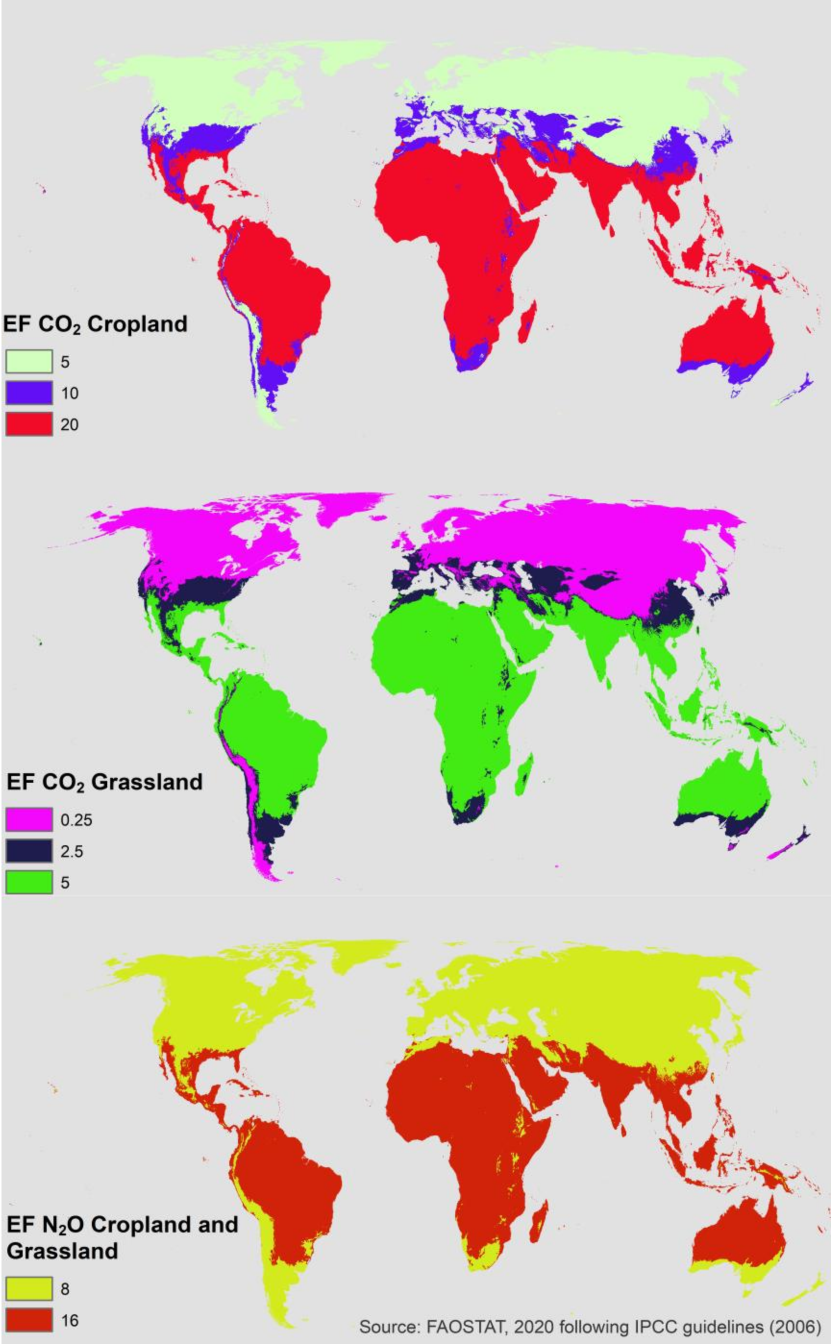


Figure 4. Climatic zones based on IPCC classification (JRC, 2010)



Source, FAO, 2020 based on IPCC climatic zones (JRC, 2010)

Figure 5. Spatial layers of emission factors from the IPCC Guidelines (2006) by gas, land use and climatic zone



695

Figure 6. Global emissions from drained organic soils, 1990–2019

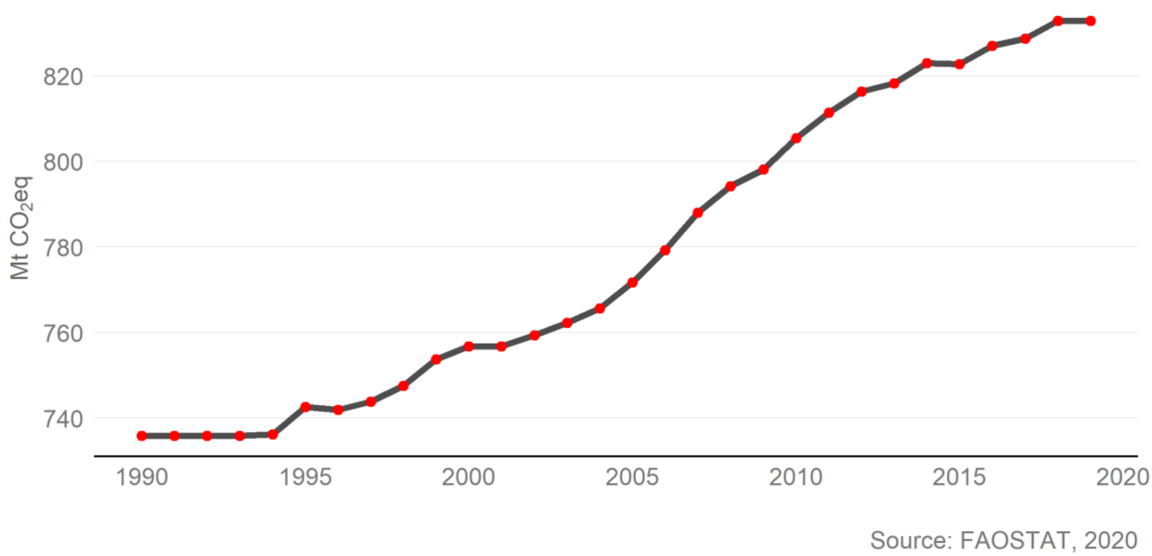


Figure 7. Top 10 countries by emissions from drained organic soils (75 percent of global emissions)

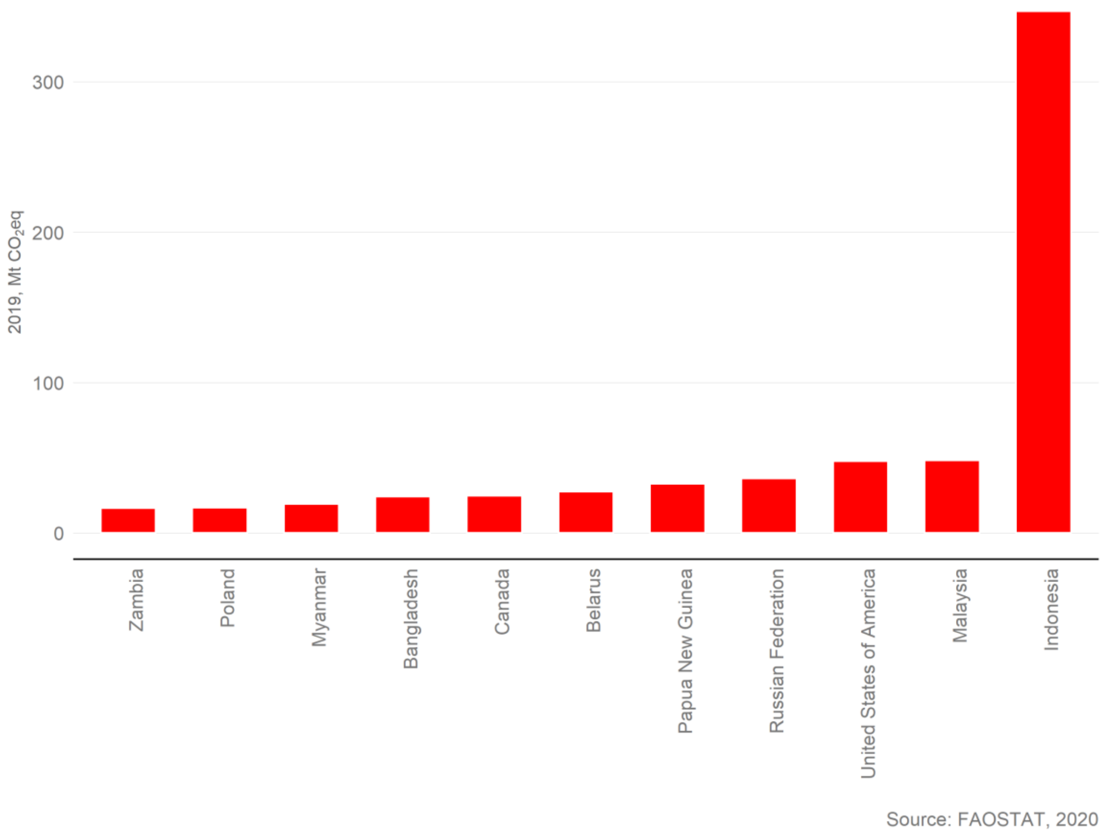


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Figure 8. Scatterplot of log-transformed area estimates for organic soils (Page et al., 2011) and FAOSTAT.

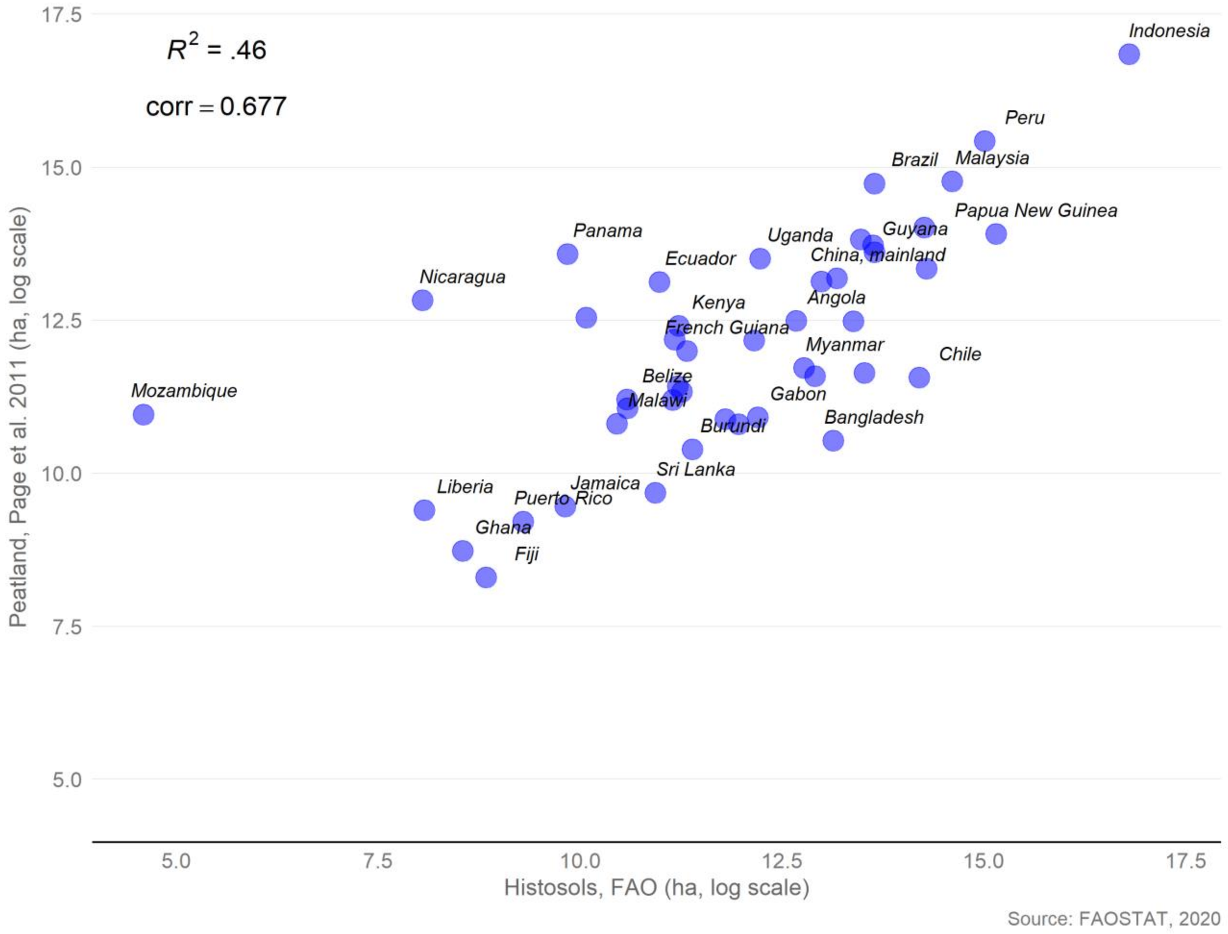


Figure 9. Scatterplot of area estimates for organic soils in published data (Gumbricht et al., 2017) and FAOSTAT. Data have been log-transformed to avoid dependence on a few large vales.

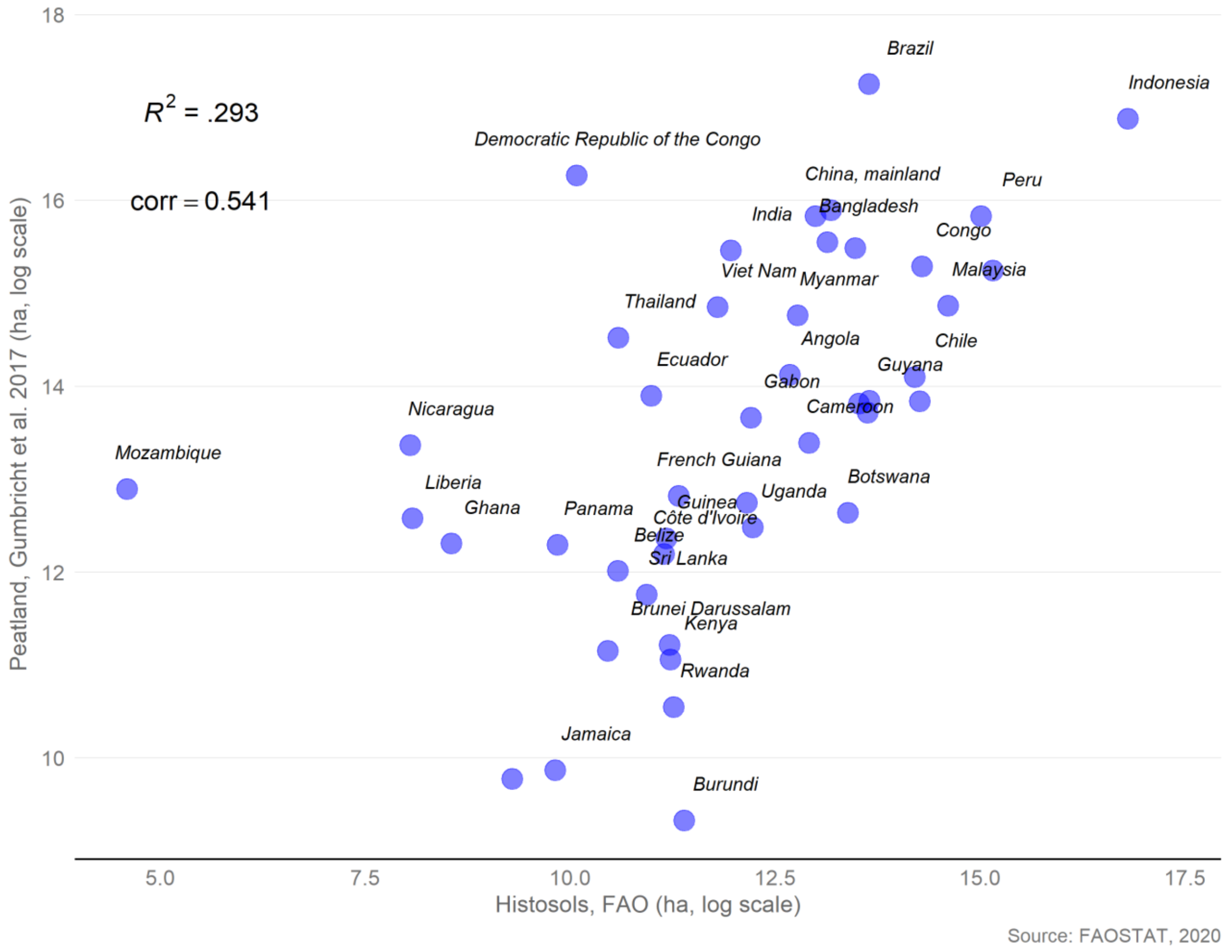


Figure 10. Comparison of FAOSTAT estimates of drained organic soils area *vs* official country data reported to UNFCCC (year 2017). Distance from predicted (on the fitted line) and actual data

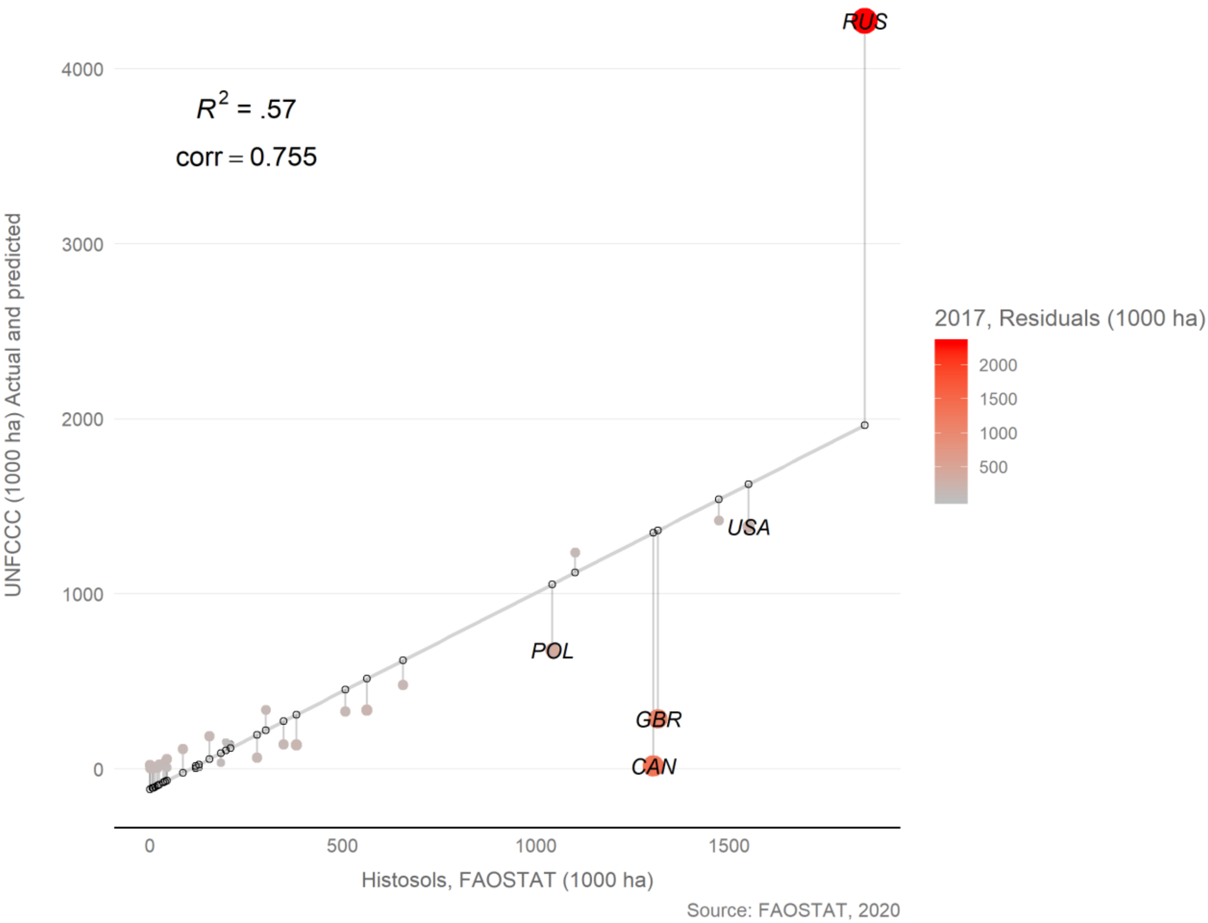
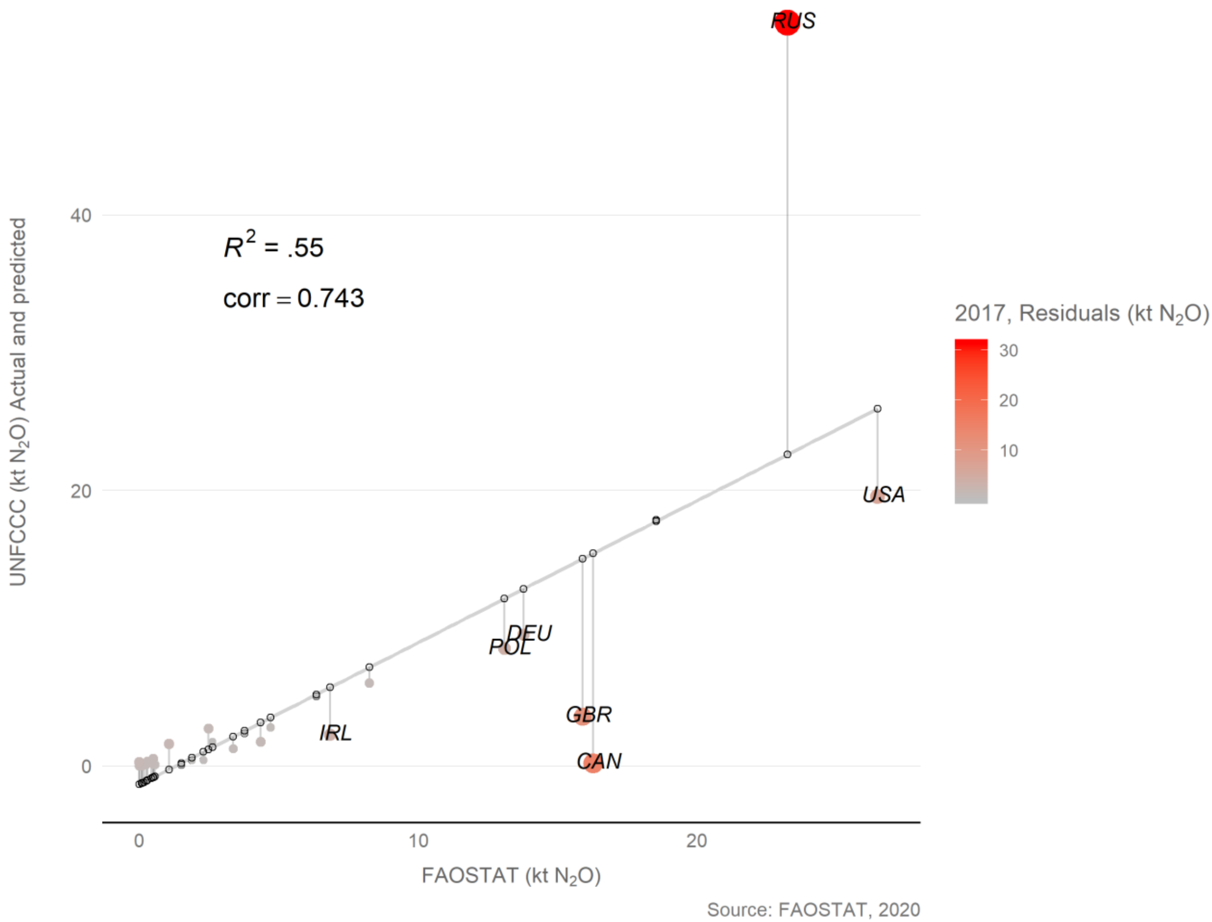


Figure 11. Comparison of FAOSTAT estimates of GHG emissions (N_2O) compared to UNFCCC data (year 2017)



730

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

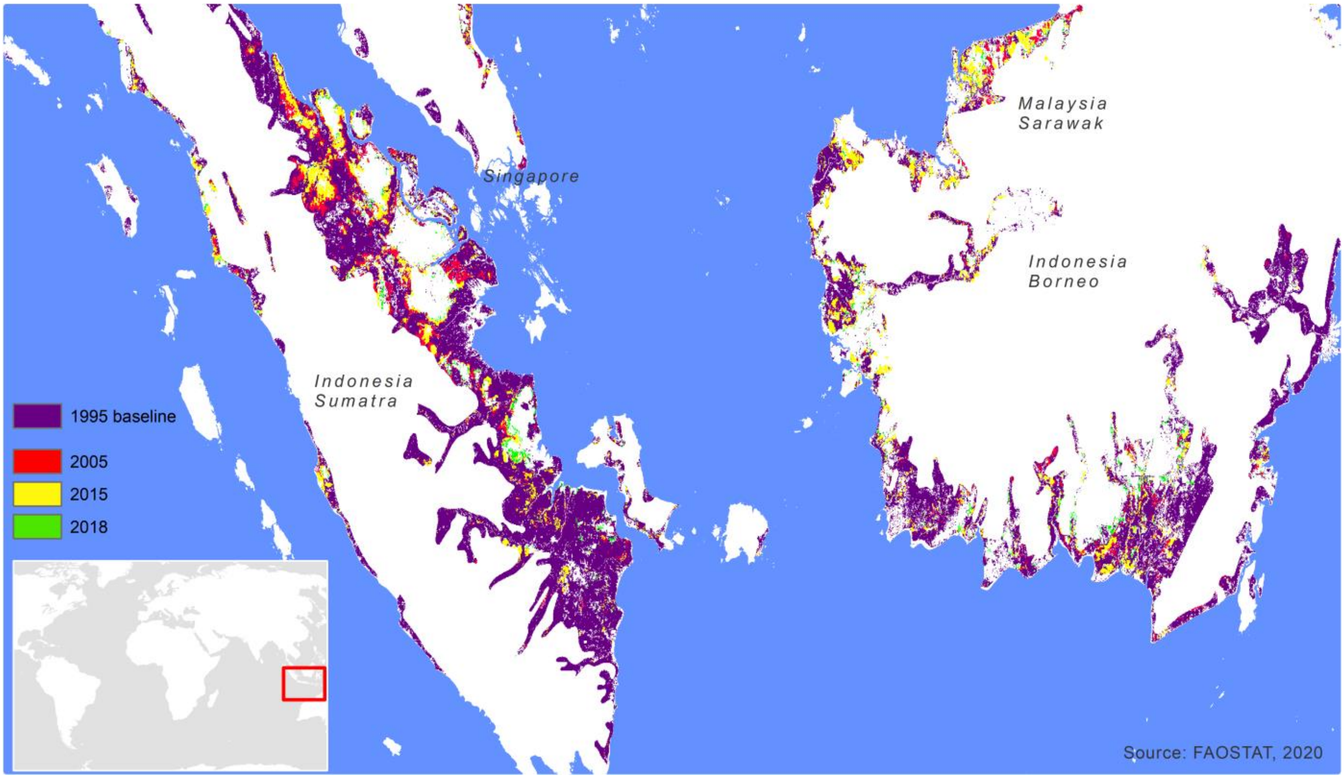


Figure 13. FAOSTAT estimates *vs* reported CO_2 emissions form the drainage of organic soils in Indonesia, 1990–2016 (2nd Biennial Update Report, 2018 submission to the Climate Convention)

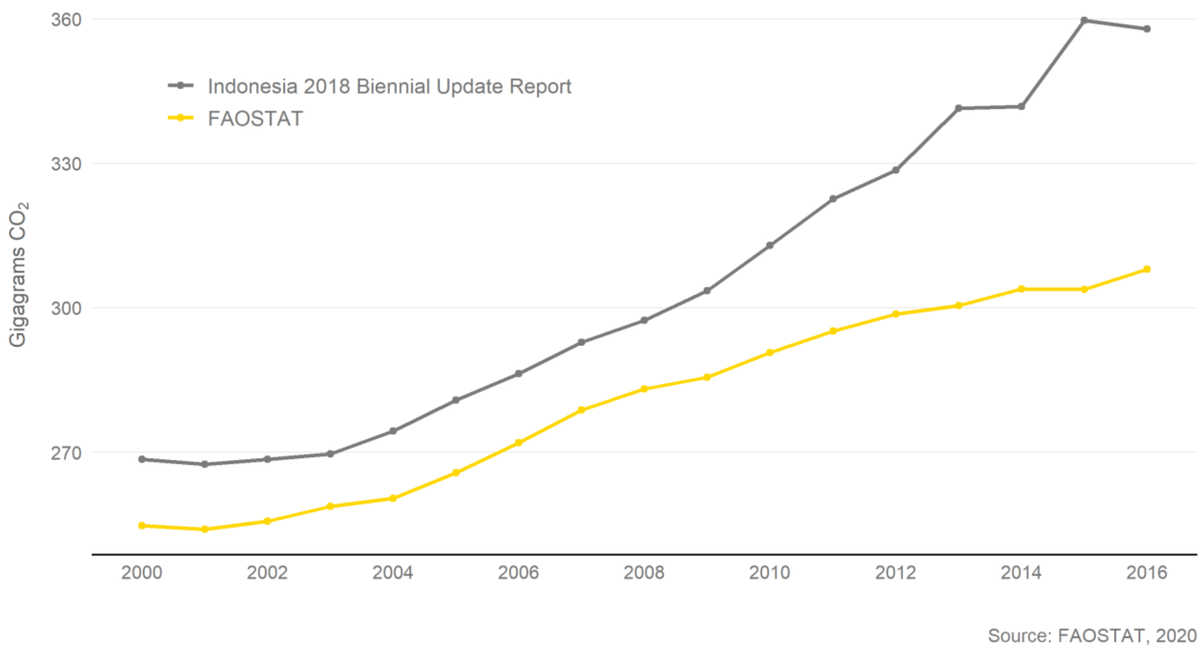


Figure 14. Oil palm and other tree plantations (Petersen et al., 2016) and FAOSTAT Cropland organic soils in 2014