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Rewetting strategies to reduce nitrous oxide emissions from European peatlands

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Nitrous oxide (N_2O) is approximately 265 times more potent than carbon dioxide (CO_2) in atmospheric warming. Degraded peatlands are important sources of N_2O. The more a peat soil is degraded, the higher the N_2O-N emissions from peat. In this study, soil bulk density was used as a proxy for peat degradation to predict N_2O-N emissions. Here we report that the annual N_2O-N emissions from European managed peatlands (EU-28) sum up to approximately 145 Gg N year^{-1}. From the viewpoint of greenhouse gas emissions, highly degraded agriculturally used peatlands should be rewetted first to optimally reduce cumulative N_2O-N emissions. Compared to a business-as-usual scenario (no peatland rewetting), rewetting of all drained European peatlands until 2050 using the suggested strategy reduces the cumulative N_2O-N emissions by 70%. In conclusion, the status of peat degradation should be made a pivotal criterion in prioritising peatlands for restoration.

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Agriculture contributes to one-quarter of the worldwide greenhouse gas (GHG) emissions[1,2]. Nitrous oxide (N_2O) is classified as a long-lived GHG and has a global warming potential of ~265 times[3] that of carbon dioxide (CO_2). It is also the main driver of stratospheric ozone depletion[4]. Nitrous oxide emissions, accounting for 46% of GHG emissions from agricultural soils, largely come from soil and nutrient management such as tillage and fertilizer application[5,6].

Peatlands cover only about 3% of the global land surface but store 21% of the global soil C pool[7] and 8–15 Gt N[8,9]. To date, at least 15% of the world's peatlands have been artificially drained for agriculture, forestry, peat extraction, and bioenergy plantations[10]. The drained peatlands are mostly located in Europe and South-east Asia[11]. Peatland drainage causes land subsidence and carbon mineralization leading to soil degradation, GHG emissions (e.g., CO_2, N_2O), and dissolved organic carbon (DOC) leaching into downstream water bodies[12,13]. It has been reported that northern peatlands may emit 30–100 Gg N_2O-N year^{-1}[14]. The world's drained peatlands cumulatively release 2.3 Gt N[8].

The N_2O production in soils originates mainly from nitrification and denitrification processes[15]. The N_2O emissions from peat are closely linked to peat type, water management, and climate zones[14,16,17]. In natural undisturbed peatlands, the N_2O emissions are generally low due to the low oxygen and/or nitrogen availability[18,19]. Peatland drainage increases N_2O emissions by enhancing the oxygen and nitrogen availability[16,18,20]. It has been reported that the well-drained and nitrogen-rich tropical peatlands are global N_2O emission hotspots[16]. The N_2O emissions from drained peatlands vary greatly because of nutrient content variations and land management. For instance, lowering the water table had no effect on N_2O emissions from nutrient-poor but increased those from nutrient-rich peatland[14]. Furthermore, several studies[19,21,22] found that N_2O emissions from cropland and grassland are generally higher than those from the forest (natural peatlands drained for forestry). However, the conversion of agriculture to forest leads to no significant reduction in N_2O emissions as compared to peat soils under active agricultural use[23]. Lastly, nitrogen, as well as phosphorus fertilizer applications, may additionally enhance N_2O emissions from agricultural peatlands[24,25].

Monitoring N_2O emissions from peatland is time-consuming and expensive[23,26]. Therefore, numerous simulation models and statistical relationships have been developed to predict N_2O emissions at multiple spatial scales[21,27,28]. In the national GHG inventories, the published IPCC default emission factors (Tier 1) have been used to estimate N_2O emissions from peatlands. Several studies reported that vegetation and soil properties (C/N; bulk density, BD) are also good proxies to estimate N_2O emissions at the field or national scales[18,21,29,30]. The C/N ratio decreases and BD increases along with soil degradation[30]. The more a peatland is degraded, the higher the N_2O fluxes[30]. Soil BD as a proxy for peat degradation was superior to other parameters (C/N, pH) in estimating annual N_2O emissions in a previous study[30] because it is an integrating parameter reflecting both physical and biogeochemical transformation processes.

In Europe, <1% of the drained peatland has been rewetted over the past decades[31]. Peatland rewetting is an effective measure to rehabilitate ecosystem functions and can reduce soil subsidence and greenhouse gas emissions (CO_2 and N_2O)[32–35]. However, little information is available on how to best prioritize drained peatlands for rewetting, to maximize the reduction of N_2O emissions. The objectives of this study were to (1) re-estimate the N_2O emissions from European drained peatlands (EU-28, 2013) using a newly generated soil bulk density map; (2) predict the N_2O emission for several decades under scenarios with different rewetting priorities.

Results

N_2O-N emissions from managed European peatlands. The managed European peatlands are characterized by a wide range of topsoil (0–30 cm) bulk density (BD) from 0.1 to 0.9 g cm^{-3} (Supplemental Fig. 1). The average (10th percentile, 90th percentile) topsoil BD of cropland, grassland, and forest was 0.7 (0.5, 0.8), 0.6 (0.4, 0.8), and 0.5 (0.2, 0.8) g cm^{-3}, respectively. This finding indicates that peatlands under cropland are more severely degraded than those under forest, which is most likely related to the deep drainage of cropland-peat-systems. The estimated average N_2O-N emission factors using BD for cropland, grassland, and forest were 19.3, 17.4, and 3.4 kg N ha^{-1} year^{-1}, respectively (Table 1), which are greater than the default values from IPCC (Supplemental Table 1). The N_2O-N emission factor for a forest is significantly lower than those for agricultural peatlands. The 95% confidence intervals (Table 1) suggest that there is no significant difference in N_2O-N emission factors between cropland and grassland.

The estimated N_2O-N emissions from European managed peatlands under different land uses were calculated to be 47.1, 61.4, and 36.6 Gg N year^{-1}, for cropland, grassland, and forest, respectively (Table 1). In this study, the overall N_2O-N emissions from European (EU-28) managed peatlands were estimated to be 145.1 Gg N, which is twice the number estimated by the IPCC approach. The N_2O-N emission hotspots (15–21 kg N ha^{-1} year^{-1}) are located in Ireland, Sweden, Poland, Germany, and The Netherlands (Fig. 1), where the organic soils are extensively drained.

Future of N_2O-N emissions from managed European peatlands. The N_2O-N emissions from European managed peatlands under different scenarios are shown in Fig. 2. Under a scenario with an expansion of drainage (scenario 1), the annual N_2O-N emission increases slightly but is within the variance range of annual N_2O-N emission of an unaltered system (scenario 2). The

Table 1 Area of managed European peatlands (×10^6 ha), BD-based N_2O-N emission factors (kg N ha^{-1} year^{-1}), and overall N_2O-N emissions (Gg N year^{-1}) for managed European peatlands (EU-28) as calculated using BD-based and IPCC emission factors for organic soils[1].

Land use	Area	N_2O-N emission factors (BD-based)			N_2O-N emission	
		Average	10th percentile	90th percentile	IPCC	BD-based
Cropland	2.4	19.3 (13.2, 26.8)	15.2 (10.7, 19.7)	20.9 (14.3, 29.5)	31.7 (20.0, 43.9)	47.1 (32.2, 65.6)
Grassland	3.5	17.4 (11.7, 26.1)	8.8 (6.7, 11.8)	20.9 (14.3, 29.5)	29.7 (16.9, 40.9)	61.4 (41.5, 92.3)
Forest	10.7	3.4 (2.0, 6.3)	0.6 (0.4, 0.8)	5.1 (2.8, 9.4)	9.8 (−0.5, 19.9)	36.6 (21.3, 66.6)
Sum	16.6	-	-	-	71.3 (36.4, 104.7)	145.1 (94.7, 223.2)

The parentheses indicate 95% confidence intervals.

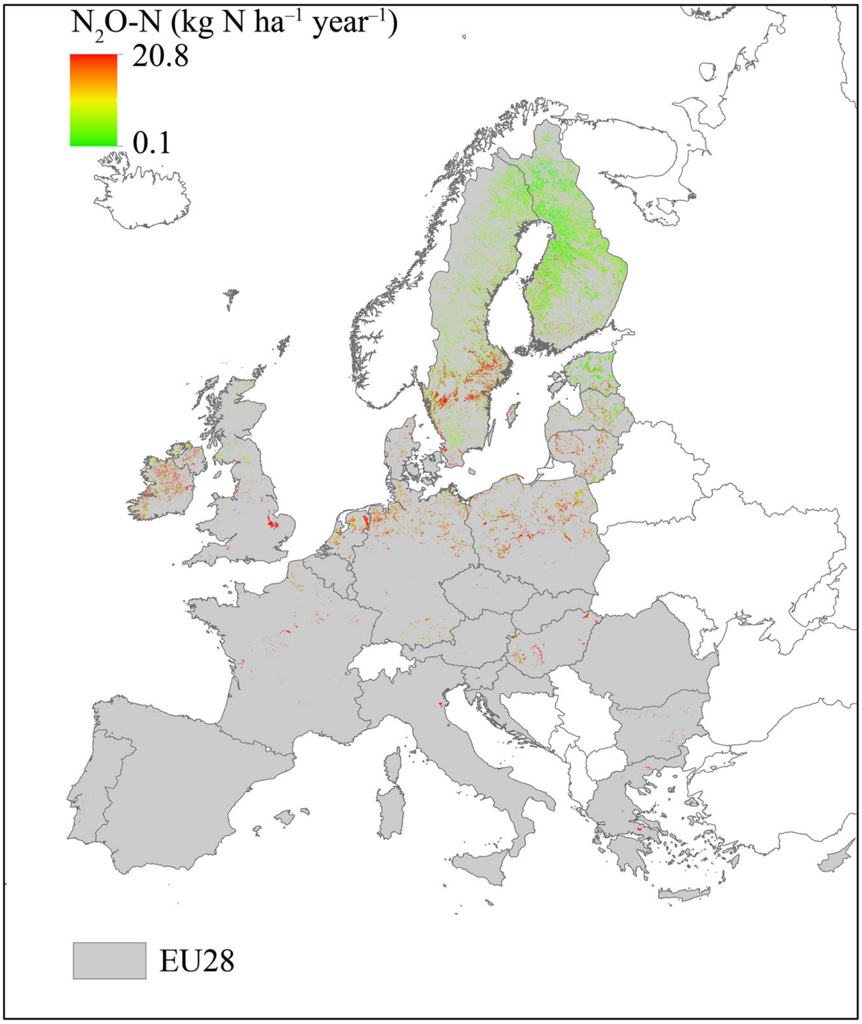

Fig. 1 Map of annual nitrous oxide (N_2O-N) emissions from managed European peatlands. The grey regions refer to the European Union in 2013 (EU28).

95% confidence intervals (Fig. 2a, b) indicate no distinct differences in N_2O-N emissions between scenarios 1 and 2 (no change scenario). Under both scenarios, the accumulated N_2O-N emissions over 30 years will add up to ~4500 Gg (95% confidence interval from 3000 to 7000 Gg). If all drained peatlands were rewetted over the coming 30 years with an annual water table at the ground surface, the annual N_2O-N emission will decrease to 0 kg N ha^{-1} year^{-1}. However, the accumulated N_2O-N emissions under scenario 4 (starting to rewet the highly degraded peatlands and rewetting agricultural peatlands first) will be substantially lower (1229 Gg N) than those under scenario 3 (3267 Gg N; starting to rewet from low to high degradation status and rewetting the forested peatlands first). Compared to the no-change scenario, cumulative N_2O-N emissions will decrease by 30% under scenario 3. However, the reduction will be 70% under scenario 4 after 30 years.

Discussion

It has been reported that IPCC underestimated the average N_2O-N emission factors for managed peatlands[19,36]. In this study, the estimated N_2O-N emission factor for croplands is similar to the values reported by previous studies ranging from 16.5 to 19.1 kg N ha^{-1} year^{-1} [19,36]. Our estimated N_2O-N emission factor for grassland is greater than the reported values ranging from 2.9 to 14.1 kg N ha^{-1} year^{-1} [19,21,37], but is within the range measured in field experiments (from 0.7 to 39 kg N ha^{-1} yr^{-1} [22,38]). Grassland management on peatland varies widely from intensively used and drained, to extensively managed and wet grassland. This wide variability in management may lead to high variance of average N_2O-N emission factors[39].

The average N_2O-N emission factor for forested peatland found here is similar to the value (3.1–4.2 kg N ha^{-1} year^{-1}) reported by Leppelt et al.[19] and within the range of 2.6 to 4.3 kg N ha^{-1} year^{-1} [37]. Leifeld stated that the average N_2O-N emission factor for forested peatland in Switzerland was 1.2 ± 3.1 kg N ha^{-1} year^{-1} with a median value of 3.0 kg N ha^{-1} year$^{[-1}$ [21]. The high variance of average N_2O-N emission factors for forested peatland is probably related to the wide C/N ratio and soil BD[21,30]. For forested peatlands, the IPCC default N_2O-N emission factor for boreal nutrient-poor forests (0.22 kg N ha^{-1} year^{-1}) seems too low for the European forested peatlands. The IPCC emission factor for boreal nutrient-rich forests is in line with the values reported here. It should be noted that the N_2O-N emission factor for forested peatlands may underestimate afforested peatlands (converted from agricultural to forest peatland).

The topsoil BD map of European managed peatlands clearly shows that most of the European drained peatlands are severely degraded. Under this situation, using IPCC default emission factors across all peatlands may underestimate the N_2O-N emission from drained peatland, especially for grassland where

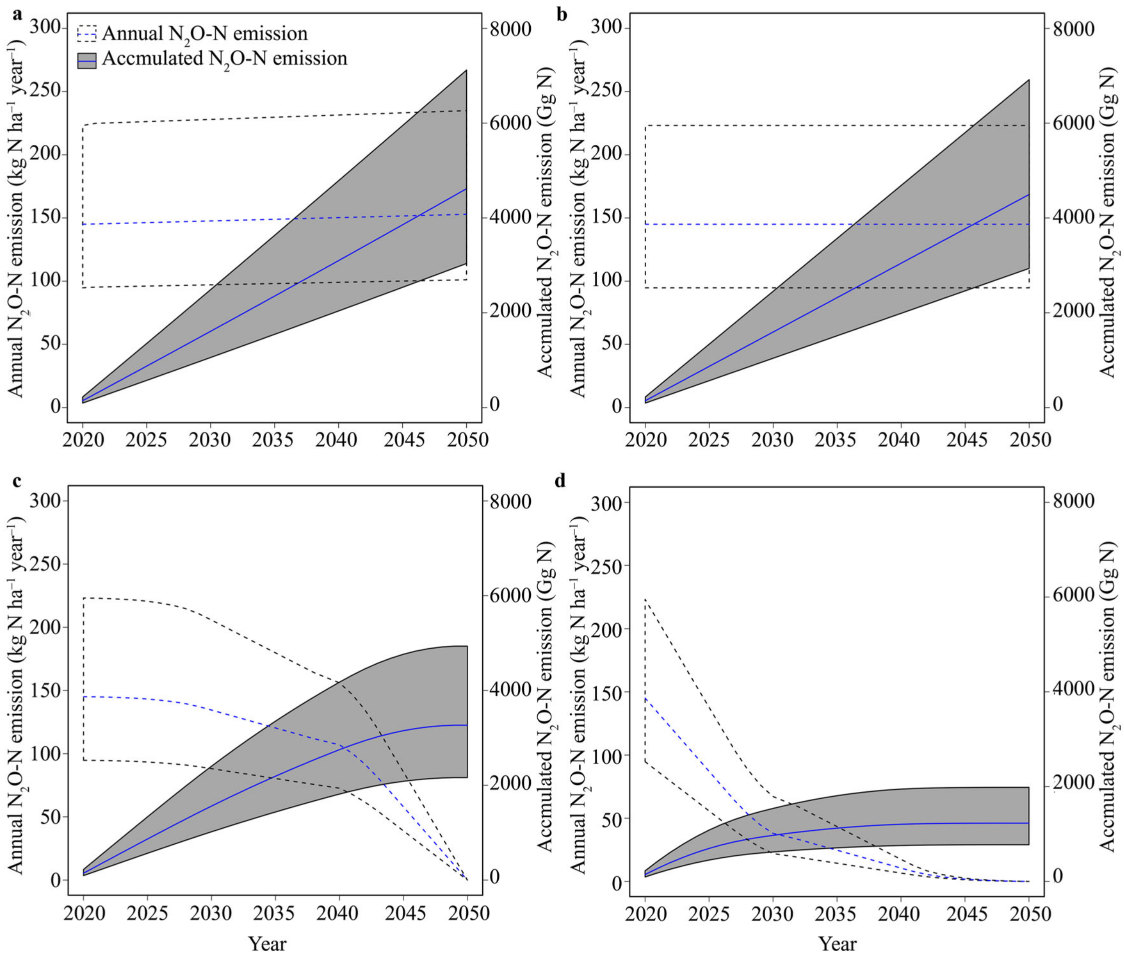

Fig. 2 Future annual and cumulative nitrous oxide (N_2O-N) emissions from managed European peatlands (EU-28) under different scenarios. a The area of drained peatland will increase continuously; **b** the area of drained peatland remains constant; **c** rewetting, starting with lowly degraded peatlands; **d** rewetting, starting with highly degraded peatlands. The shaded areas indicate 95% confidence intervals.

organic soils are strongly disturbed and extensively drained. The estimates as presented here take soil degradation (soil BD) explicitly into account and are, thus, considered superior to IPCC default emission factors.

Here, we estimated the effect of different peatland management scenarios on future N_2O-N emissions. It is surprisingly found that if the area of artificially drained peatland is expanded by 30%, the N_2O-N emissions will not significantly increase in the near future (<30 years). The estimated N_2O-N emissions from these newly drained peatlands are comparable to natural and undrained peatlands (0.01 to 1.6 kg N ha^{-1} $year^{-1}$ [26,40]). One possible reason is that the carbon mineralization rate is lower at the early stage of peatland drainage[41], and a relatively large soil C/N ratio is maintained, which constrains N_2O emissions from peat[18,42].

The effect of rewetting measures on N_2O-N emissions is related to the groundwater table height[30,43]. Despite a huge variability in N_2O-N emissions, it is very clear that the emissions are approaching 0, if the average annual water table is near or above the ground surface (Fig. 3). For rewetted and degraded peatlands with an annual water table of 10–30 cm below ground surface, the topsoils suffer both aerobic and anaerobic conditions, allowing N_2O-N emissions from both nitrification and denitrification processes[30]. Therefore, if the peatlands are not properly rewetted, the accumulated N_2O-N emissions from European managed peatlands remain comparable to scenarios 1 and 2.

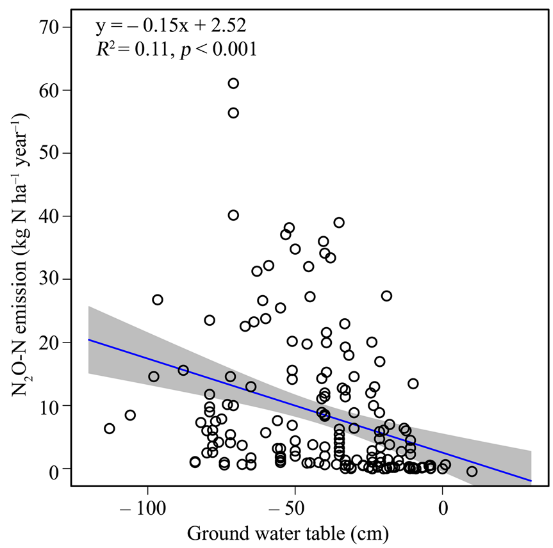

Fig. 3 Scatter plot of annual nitrous oxide (N_2O-N) emissions from peatlands against the annual groundwater table. The data are from Liu et al.[30] and Höper et al.[43].

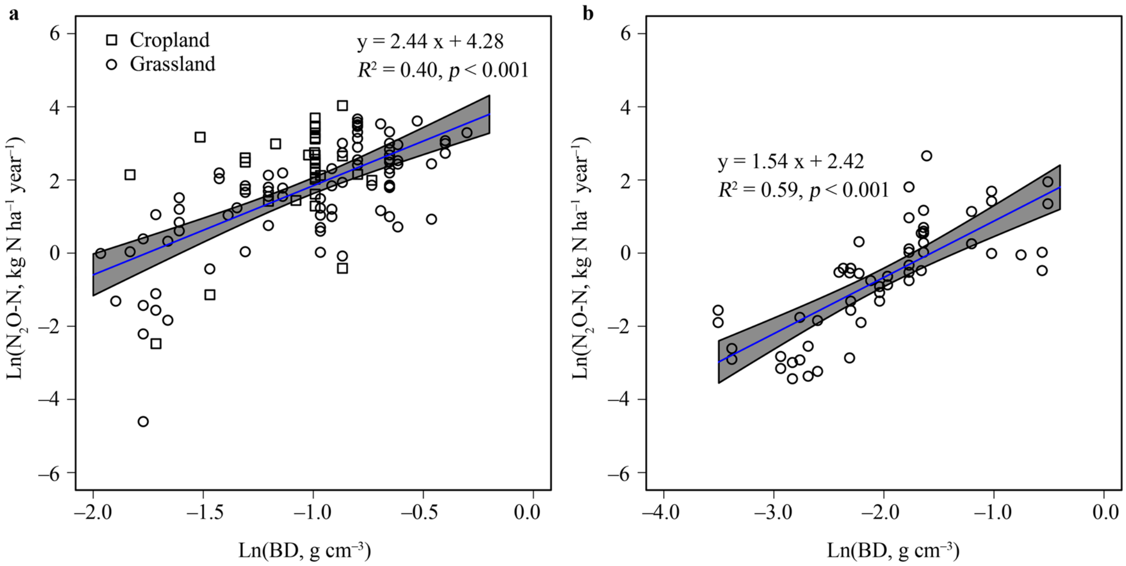

Fig. 4 The relationships between annual nitrous oxide (N_2O-N) flux from peatlands and topsoil bulk density (BD). **a** Agricultural peatlands (cropland and grassland); **b** forested peatlands. Data are from Liu et al.[30]. The shaded areas indicate 95% confidence intervals.

It is necessary to estimate the cumulative GHG emissions of CO_2, CH_4, and N_2O, if peatland restoration strategies are to be evaluated because the gases factually accumulate in the atmosphere[37,44]. Figure 2 suggests that peatland rewetting starting from highly to lowly degraded peatlands and from agricultural to forested peatland is the most effective strategy to reduce the cumulative N_2O-N emissions. This strategy is likewise supposed to be effective in reducing cumulative CO_2 emissions because the strongly disturbed and extensively drained agricultural peatlands, recognized as highly degraded peatlands, are also emitting CO_2 at high rates[25,45]. Several studies reported that rewetting of highly degraded peatlands is a major challenge especially for the biodiversity targets and suggest lightly degraded peatlands should be prioritized for rewetting from an economic and biological viewpoint[32,46]. However, most managed peatlands in Europe are in a high degradation stage and they emit most of the GHG of all peatlands. Postponing rewetting of these highly degraded soils may increase the long-term warming effect through continued GHG emissions. The most effective restoration strategy should be further evaluated in future studies in an interdisciplinary approach.

To our knowledge, this is the first time that a bulk density map for soils was generated and used to estimate the N_2O-N emissions from managed European peatlands. Our work is in line with studies showing that the drained peatlands in Europe are in a stage of severe degradation and suggests that they emit considerable amounts of N_2O-N. Less than 6×10^6 ha of agriculturally used peatlands (cropland and grassland) emit over 100 Gg N_2O-N year^{-1}, equivalent to 25 % of soil N_2O emissions from the entire agriculture land of EU-28[47]. In this study, the estimated N_2O-N emissions from European managed peatlands are twice the value of those calculated using IPCC default emission factors. The results suggest that the best restoration strategy to reduce cumulative N_2O-N emissions is to rewet highly degraded peatlands first before attending to those with a low degradation status. Such a strategy would result in a cumulative reduction of N_2O-N emissions from European peatlands by 70% over the next 30 years as compared to business as usual. Only a 30% reduction will be achieved if rewetting is initiated at less degraded peatlands first. This study provides a new perspective on how to prioritize peatland restoration strategies. However, the quality of the BD map needs to be improved and more data is required on N_2O-N emissions from highly degraded peatlands to reduce prediction uncertainty.

Methods

N_2O emissions from managed European peatlands. The European peatland map[48], European land use map[49], and European topsoil OM map[50,51] were used to estimate the BD of topsoils for managed European peatlands. The BD map of European peat topsoil (0–30 cm) was derived from the OM map using a pedo-transfer function (BD = −0.008OM + 0.867; $R^2 = 0.84$; $n = 941$; BD, g cm^{-3}; OM, % by weight[30]; Supplemental Fig. 2 and Supplemental Table 2). The topsoil OM map of Croatia was derived from the topsoil organic carbon map[51] by applying a factor of 1.72.

The N_2O-N emissions from managed European peatlands were estimated based on the derived BD map for peatlands and the relationship between soil BD and annual N_2O-N emissions (Fig. 4[30]). The data set from Liu et al.[30] shows that most of the high N_2O-N emission values (>10 kg N ha^{-1} year^{-1}) for forested peatlands originate from afforested formerly agriculturally used peatland[23]. For forested peatlands without any cultivation history, the N_2O-N emissions are generally <7 kg N ha^{-1} year^{-1}. Therefore, we apply different BD-N_2O-N functions for agricultural and forested peatlands (excluding afforested agricultural peatlands). The N_2O-N emissions from afforested peatlands on former agricultural sites are comparable to those from agriculture before conversion; this rare situation was excluded from the study. The relation between soil BD and annual N_2O-N emissions did not differ between grassland and cropland. Therefore, we assume that N_2O-N emissions from grassland and cropland follow the same function with soil BD. For peat soils with a BD of 0.6 g cm^{-3}, N_2O-N emissions from cropland, grassland, and forested peatland were 20.8, 20.8, and 5.1 kg ha^{-1} year^{-1}, respectively (Fig. 4). Little information is available on N_2O-N emissions from peat soils with BD > 0.6 g cm^{-3}, therefore, for these soils we set a fixed value of 20.9 (14.3, 29.5), 20.99 (14.3, 29.5), and 5.1 (2.8, 9.4) kg N ha^{-1} year^{-1} for cropland, grassland, and forested peatland, respectively. We used the standard errors of the coefficient estimates from the statistical models to calculate the 95% confidence intervals.

Default emission factors from IPCC[1] were also applied to compare with the results using BD functions. The average N_2O-N emission factor (95% confidence interval) for boreal and temperate cropland was set to 13.0 (8.2, 18) kg N ha^{-1} year^{-1}. The average N_2O-N emission factor (95% confidence interval) for boreal and temperate grassland on peatland was set to 9.5 (4.6, 14) and 8.2 (4.9, 11) kg N ha^{-1} year^{-1}, respectively. The average N_2O-N emission factor (95% confidence interval) for boreal and temperate forested peatlands was set to 0.22 (0.15, 0.28) and 2.8 (−0.57, 6.1) kg N ha^{-1} year^{-1}, respectively. Nutrient and drainage conditions are not available in a spatially explicit way; therefore, we assumed nutrient-poor conditions for boreal forests and nutrient-rich conditions for temperate forests. We also assumed deep drainage conditions for temperate grasslands[19].

Future of N_2O emissions from managed European peatlands. In order to estimate the N_2O-N emissions from a managed peatland in future, the following scenarios were considered: (1) a continuously increasing area of drained peatland with 160,000 ha of additionally drained area per year (1% increase of drained peatland area per year[52]); (2) the area of drained peatland remains constant; (3) rewetting of all drained peatland until 2050 beginning with peatlands that are least degraded to those with a high degradation status and from forested peatlands to agricultural peatlands (3.3% of drained peatland or 554,300 ha $year^{-1}$); (4) rewetting of all drained peatland until 2050 in the order of highest to lowest degradation stages and from agricultural peatlands to forested peatlands (3.3% of drained peatland or 554,300 ha $year^{-1}$). For scenario (1), the topsoil BD of newly drained peatlands was estimated using a function between BD and peatland drainage years[53]. After 30 years of drainage, the soil BD is expected to increase from 0.1 g cm^{-3} to 0.15 and 0.26 for forested and agricultural peatland, respectively. We estimate that with these BD values, the N_2O-N emissions from forested and agricultural peatland were 0.6 (0.5, 0.9) and 2.7 (2.0, 3.5) kg N ha^{-1} $year^{-1}$ (after 30 years). We assume that the status of already degraded peat soils does not change within the 30 years for scenarios (1) and (2). For scenarios (3) and (4), we considered that the world has to reach zero GHG emissions by 2050[54].

Data availability

The European peatland map is freely available from http://archive.researchdata.leeds.ac.uk/251/. The European topsoil OM map is available from https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/efsa-spatial-data-version-11-data-properties-and-processing. European Land use map used in this study is available under https://doi.pangaea.de/10.1594/PANGAEA.896282. The data set containing N_2O-N emissions, bulk density, water table, and soil organic matter content is available from https://doi.org/10.17632/2khr7kh55m.2.

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