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Research article

Mapping peatland extent and condition in the conterminous United States and Hawaii to inform peatland protection and restoration

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ABSTRACT

Peatland conservation and restoration are globally important goals because of peatlands' potential to sequester and store carbon for millennia, regulate hydrology, and emit greenhouse gases (GHGs) when degraded. To provide information that can be used to identify possible targets for restoration, we have developed a peatland condition map for the conterminous US and Hawaii using existing GIS-based information. We intersected gSSURGO histosols and histic epipedons (HE) with layers for land use, crops, ditches, roads, and railroads (within 150 m buffers for the last three), land protection classes, and USDA Natural Resources Conservation Service (NRCS) wetland easements. Of the 94,750 km^2 of histosols and 13,533 km^2 of HE analyzed, 7 % (7709 km^2) were under agricultural use. Of 100,415 km^2 of histosols and HE not in agricultural use, 19 % were within 150 m of ditches, roads, or railroads. Of mapped histosols, 38 % (36,042 km^2) were legally protected from extractive use, and 635 km^2 were in NRCS wetland easements. Based on IPCC tier 1 emission factors, the greatest reduction of CO_2-e emissions per unit area and nationally would be from rewetting of peatlands under agriculture. In non-agricultural areas, rewetting peatlands affected by ditching alone is likely more cost-effective than if they are also affected by roads and railroads. Total potential emission reduction associated with rewetting of currently analyzed drained peatlands is estimated at >36.8 Tg CO_2-e yr^{-1}. Future gap filling of the map will likely increase this estimate. This map can be used to evaluate potential peatland restoration opportunities at a variety of scales.

1. Introduction

Peatlands are the most carbon (C) dense terrestrial ecosystems globally (Yu et al., 2011) because of their capacity to accumulate C as partially decomposed organic matter (peat) over millennial timescales. This property depends on several factors, among which near-continuous water saturation of the soil is the most important, as it constrains decomposition more than primary production, leading to long-term net inputs of organic matter (Limpens et al., 2008). Hence, any disturbance to peatland hydrologic integrity (e.g., ditching, tiling for agriculture, roads, railroads) leads to increases in decomposition which can reduce the sink strength of peatlands for CO_2, and cause net emission of greenhouse gases (GHGs) to the atmosphere (Limpens et al., 2008; Yu et al., 2011).

In addition to drainage, conversion to agriculture and associated fertilization can enhance GHG emissions, especially of nitrous oxide (N_2O). The combination of drainage and fertilization consistently increases rates of N_2O emissions on peat soils (Lin et al., 2022). This is especially concerning because the global warming potential of N_2O is roughly 265 times higher than that of CO_2 over a 100-year time period (Myhre et al., 2013).

Protection of intact peatlands, and restoration of degraded peatlands, have been identified as two highly impactful Natural Climate Solutions (NCS) globally (Griscom et al., 2017) and in the US (Fargione et al., 2018). Although the GHG emissions from drained peatlands (EPA, 2024) and the potential benefit of protection and restoration of peatlands have been estimated (Fargione et al., 2018), surprisingly, high resolution maps combining peatland location and condition for the US have not yet been developed. Such maps are essential to assess the status of peatlands nationally, and to inform decisions regarding peatland protection or restoration.

Various programs in the US focus on protection and restoration of wetlands, e.g. via the USDA's Natural Resource Conservation Service (USDA-NRCS) Agricultural Conservation Easement Program (https://www.nrcs.usda.gov/programs-initiatives/wre-wetland-reserve-

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Glossary

EF	Emission factor, an annualized areal estimate of emissions of a particular gas under certain conditions. Typically expressed in tonnes (Mg) of CO_2-equivalent gas per hectare-year
ER	Emission reduction, an annualized areal estimate of the effect of intervention on emissions of a particular gas or dissolved organic carbon (DOC). Typically expressed in megagram (Mg) or metric tonnes of CO_2-equivalent (CO_2-e) per hectare-year
Tg	Teragrams
CO_2-e	Carbon dioxide equivalents in terms of global warming potential, used to compare the impact of different greenhouse gases (GHGs) on climate over a specified period of time; in this paper we use 100 years

easements). These programs allow landowners to restore the integrity and function of wetlands that have been altered by agricultural practices. Historically these programs have not specifically considered whether the agricultural lands being restored in their programs were on peat soils. In order to identify the extent of peatlands restored in these programs, to evaluate the impact of restoration on peatland condition, and to allow peatland restoration to be considered for inclusion in project prioritization and planning, it is necessary to map the peat soils (histosols) already in the program, and to assess whether new easements may provide GHG emission reduction and C sequestration that have not yet been included in project evaluation.

In the present study, we provide spatially-explicit information on the current state of peatlands in the US (excluding Alaska), and on the potential for peatland restoration. We first developed a peatland map for the conterminous 48 US states (CONUS) plus Hawaii, and intersected it with different land uses and other anthropogenic disturbance factors. Second, we assessed the geographic patterns of peatland degradation, and the extent of NRCS easement programs on peatland restoration on agricultural soils. Third, we estimated the GHG emissions from these land uses. Last, we introduce an interactive map that may inform wetland conservation and restoration prioritization. We sought to answer the following questions. Where are peatlands in the US? Where are they most degraded? What are the major causes of peatland degradation? Where are the largest opportunities for peatland restoration in terms of potential emission reductions?

2. Methods

Our map of peatland extent is based on the USDA NRCS soil survey gSSURGO raster data (derived from SSURGO polygons; Soil Survey Staff, 2020) for peatland-associated histosol classes (all histosols except folists, and all hydric histic epipedons (HE from here forward); Soil Survey Staff, 1999). Although HE are not typically considered peatlands in the working US definition because they are shallower (typically 20–40 cm thickness of the organic layer in the top 100 cm vs. >40 cm thickness for histosols), we include them as a separate map layer here because they harbor significant carbon stocks, can be significant sources of emissions, and are commonly included in the peatland definition of many other countries.

There are gaps in the gSSURGO layer that make up ~5 % of CONUS and are concentrated on public lands in the Western US (Fig. 1, Table S1). Although of ecological importance, peatlands in these areas, mostly in small mountain fens (Chimner et al., 2010), are found at much lower density than those in the mapped areas. Efforts are underway to fill these gaps using remote sensing and ground truthing-based mapping that will inform later iterations of our map.

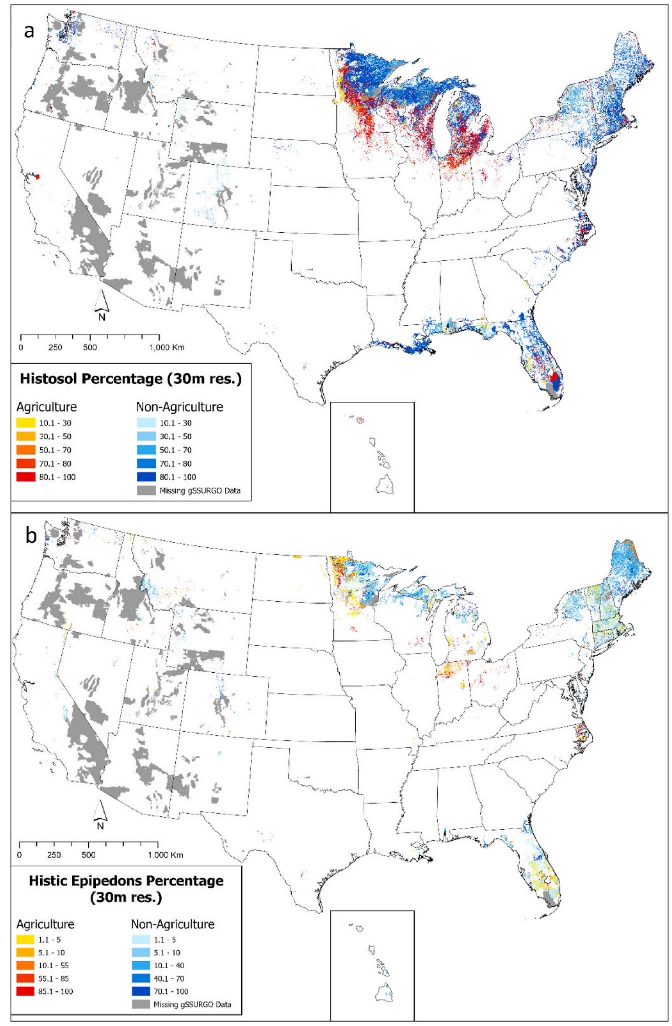

Fig. 1. Map of a) histosols and b) histic epipedons in CONUS + Hawaii, illustrating the percentage of polygons they represent, and their agricultural or non-agricultural land use. Gray areas represent the portions of the mapped area that did not have gSSURGO data, and so were not mapped for peatlands.

We chose to use the histosol layer rather than the US National Wetlands Inventory (NWI) because the latter included only lands still classed as wetlands, whereas the soil survey data include histosols on both persistent wetlands and those on former wetlands converted to other uses, mainly agriculture, as evidenced by the presence of hydric histosols on agricultural lands. Additionally, the histosol layers are based on similarity to pedons measured for organic soil depth, whereas the NWI is based largely on image interpretation. Given the high degree of degradation and potentially large GHG emissions, drained agricultural peatlands would be high priority restoration targets and so were important to capture in this analysis.

Soil survey data are defined in polygons in SSURGO (vector) and in pixels which inherit the properties of these polygons in gSSURGO (raster). These properties include soil taxonomic classifications under the data field "major components" and optionally under another field, "minor components." Typically only major components are mapped. Soil survey data are mapped in complexes that sometimes include a mixture of histosol and non-histosol soil series, so mapped histic polygons include a percent value which indicates the percentage of the feature mapped as histosol. The gSSURGO raster dataset (30 m resolution) assigned the percent histosol value from the SSURGO polygon to each 30 × 30m pixel. For histosols, we did a detailed analysis using histosols identified as major components. Minor components, which represent ~8 % of histosol area nationally (Table S2), are provided as a separate map layer but not included in the following analyses. For histic epipedons, we included both major and minor components in the intersection analysis because we believe that histic epipedons, being marginal types of peaty soils, populate the minor components field proportionally more often than histosols do.

To determine which histosols had been altered by land use change, we intersected the histosol data with land use and land cover data from the 2019 National Land Cover Database (NLCD) and the 2020 cropland data layer (NASS CDL) for CONUS. To determine pasture/hay impacts on peatlands, we created a hybrid layer of NASS and NLCD data, given the undersampling of this class in the NASS database (USDA-NASS, 2020). To determine the extent to which other anthropogenic changes had influenced peatlands, we also intersected drainage features, roads, and railroads. The ditch drainage features were derived from USGS NHD datasets. The roads and railroads were derived from OSM (OpenStreetMap) datasets (see Supplementary Methods for details).

Buffer width for ditch intersections was 150 m, based on our previous analysis of ditch influence zones (Krause et al., 2021). The width of the buffer zone for railroads and roads was also set at 150 m. Although the effect of the latter on peatlands is highly variable (Williams-Mounsey et al., 2021), we found no quantification of the scale of impact, so we set the level the same as that of the ditches in order to simplify comparison.

To characterize the effect of land protection status on peatland condition, we used the Protected Area Database (PAD-US) layer, which divides protected areas into four protection classes: Status 1, permanent protection from conversion, subject to natural disturbance (e.g., Wilderness Areas); Status 2, permanent protection from conversion, some suppression of natural disturbance (e.g., National Wildlife Refuges); Status 3, permanent protection for most of the area, some extractive uses allowed (e.g., National Forests); and Status 4, no known protections from conversion to other uses (e.g., private lands, agricultural areas). See https://www.usgs.gov/programs/gap-analysis-project/science/pad-us-data-overview for more details. Note some land area is not covered in the database. We treated that as a fifth class for this analysis.

To determine the influence of NRCS wetland easement programs, we obtained current easement data from NRCS as of 10/14/2021. We only included Wetland Reserve Program (WRP) and Agricultural Conservation Easement Program - Wetland Reserve Easement (ACEP-WRE). We intersected these easements with the data layers to assess how many easements included histosols and to get an estimate of the area of histosols for the easements.

To determine the influence of land use on GHG emissions, we applied the IPCC, 2006 Guidelines for National Greenhouse Gas Inventories and 2013 Wetlands supplement tier 1 emission factors (EFs) (IPCC, 2006; IPCC, 2014) to histosols and histic epipedons. To do this we had to map the emission factors onto different NLCD land use/land cover, climate, and soil properties (Table S9). For the purpose of estimating the potential emission reductions (ERs) of rewetting, we calculated the difference between the “drained” EF and the appropriate “rewetted” EF for all histosol and HE polygons. Specifically,

$$ER_{tot} = \left((EF_{CO2} + EF_{DOC} + EF_{CH4} + EF_{N2O})_{drained} - (EF_{CO2} + EF_{DOC} + EF_{CH4} + EF_{N2O})_{rewetted}\right) * \text{H\%}/100 * 0.09 \text{ ha}/pixel$$

Where ER_{tot} is the total potential emission reduction for that pixel in Mg CO_2-e ha^{-1} yr^{-1}, EF is the default Tier 1 IPCC emission factor for a pixel as derived from our NLCD/climate/soil richness classes (Table S9); CO_2 is carbon dioxide, DOC is dissolved organic carbon, CH_4 is methane, and N_2O is nitrous oxide, all EFs expressed in 100 year CO_2 equivalents ha^{-1} yr^{-1}; H% is the histosol or HE percentage for each pixel, derived from gSSURGO; and 0.09 ha/pixel is the area of each 30 × 30 m pixel. To derive an emission reduction estimate for a given area, the ER_{tot} values for each pixel contained in that area are summed (see Supplementary Methods for additional details). This method treats histosols and HEs equally, but we have kept the categories separate to allow for selective use of one or both layers. Potential ERs were calculated with the assumption that restored lands are completely rewetted and ditches filled and revegetated, not only blocked. Without ditch filling estimated ERs would differ because the IPCC provides tier 1 EFs for CH_4 specifically for ditches, which emit CH_4 at much higher rates than degraded or rewetted peatlands. For potential ERs from ditch blocking, see Supplementary methods and Table S9.

Statistical analysis. To calculate the area of histosols under any land use, we multiplied the pixel percent of histosol x the number of pixels, and converted those to standard area units (m^2, ha, km^2). We summarized several ways for each state with mapped histosols: histosol percentage by land use, specifically on agricultural and non-agricultural lands and also by the top 20 crops on peatlands; the intersection of peatlands with buffered linear features (ditches, roads, railroads) and combinations of features; NRCS wetland easements on peat; and the estimated emissions and potential emission reductions. We also developed an online version of the map at https://peatlands.mtri.org/.

3. Results

3.1. Peatlands and land use

We mapped 94,750 km^2 of major component histosols (Table 1) and 13,533 km^2 of HEs (Table S3) in CONUS + Hawaii. Including 8291 km^2 of minor component histosols (Table S2) increases the total histosol area to 102,861 km^2, and total histosol plus HEs to 116,447 km^2. The top ten states for peatland area (90 % of all histosols and HEs) were in the Lake States (Minnesota, Wisconsin, Michigan), Southeastern States (Florida, Louisiana, North Carolina, Georgia) and Northeastern States (Maine, New York, New Jersey) (Table 1, Table S3, Fig. 1).

Of the major component histosols estimated for CONUS + Hawaii, intersection with NLCD showed that 5717 km^2 (6.0 %) were under cropping, and 1177 km^2 (1.2 %) were under pasture/hay, for a combined total of 6894 km^2 (7.3 %; Fig. 1, Table 1). An additional 2032 km^2 (2.1 %) of histosols were under some level of development (Table 1). Using NASS data, a slightly lower 5362 km^2 (5.7 %) of histosols were identified as under cropping (Table S4). Dominant agricultural uses of histosols, comprising 90 % of the agriculture on histosols, were (in descending order) corn, sugarcane, pasture/hay, soybean, fallow, and alfalfa (Table S4). Virtually all of the sugarcane was in Florida, whereas other crops were more widely distributed.

Distribution of HEs among states differed somewhat from histosols, especially for Maine, which had a very high proportion of HEs (Fig. 1b) relative to histosols (Fig. 1a). Similar to histosols, when intersected with NLCD data, about 7.8 % (1055 km^2) of HEs were under cropping, 2.1 % (289 km^2) under pasture/hay, and 3.6 % (482 km^2) were developed (Table S3). Top agricultural uses of histic epipedons, comprising 87 % of the agricultural uses, were (in descending order) soybean, corn, pasture/hay, other crops, spring wheat, and sugar cane (Table S5).

3.2. Peatlands and linear disturbances

The majority (93 %) of all histosols were not under agriculture. Of just these non-agricultural histosols, 81 % was >150 m from ditches, roads, or railroads, and 19 % was <150 m from one or more of these features: 12 % was within 150 m of roads, 5 % was within 150 m of ditches, <1 % was within 150 m of railroads, and 1.8 % was within 150 m of two or more of the linear features (Fig. 2a, Fig. S1, Table S6). Similarly, 90 % of HEs were not under agriculture. Of just these non-agricultural HEs, 24 % were within 150 m of some combination of roads, ditches, and railroads (Fig. 2b–Table S7). States varied greatly in these percentages, with three states (California, Indiana, Illinois) having over 50 % of their peatlands within the 150m buffer of one of these features (Table S5). Ditched non-agricultural peatlands not affected by roads or railroads are usually easier to restore. Nationally, this category

Table 1
Major component histosol area (km^2) by state for NLCD land cover classes. Some classes have been merged. States are ordered from highest to lowest percent of total area. Six states with no histosols mapped are not included (Arkansas, Kansas, Kentucky, Missouri, Oklahoma, and Tennessee). "Pct total area" column and row are the percentage of total peatland area represented by that state or cover class, respectively.

State	Woody wetl.	Herb. wetl.	Forest/ shrub	Open water	Grassl./ herb.	Barren/ ice	Cult. crops	Past./ hay	Dev., open space	Dev. low int.	Dev., med. int.	Dev., high int.	Total area	% total area
Minnesota	15,451	7240	917	244	39	3	1019	449	196	100	42	9	25,708	27.2
Michigan	12,118	709	451	57	13	5	591	59	211	115	34	7	14,370	15.2
Florida	5934	4465	285	156	30	15	1693	206	159	114	92	28	13,178	13.9
Wisconsin	8168	2309	538	69	12	2	574	177	131	53	16	4	12,053	12.7
Louisiana	551	5489	1	457	6	5	3	27	7	33	37	12	6629	7.01
North Carolina	3916	567	166	35	25	1	385	4	38	10	4	1	5153	5.45
Maine	2212	341	396	18	8	1	1	2	17	10	4	1	3011	3.18
New York	1702	257	397	38	6	1	85	24	31	16	8	2	2567	2.71
Georgia	1315	39	6	3	2	0	2	0	1	0	0	0	1369	1.45
Massachusetts	681	168	92	13	2	2	35	3	40	28	17	3	1085	1.15
New Jersey	477	514	14	25	1	1	5	3	15	14	7	3	1079	1.14
Indiana	291	69	49	8	4	1	530	41	24	21	12	4	1052	1.11
New Hampshire	433	65	107	11	2	1	0	2	13	10	5	1	650	0.69
Maryland	146	402	2	37	0	0	2	0	4	5	1	0	599	0.63
Mississippi	368	149	43	9	2	1	0	3	9	5	2	1	591	0.63
Alabama	439	61	64	3	3	1	1	2	6	3	2	0	585	0.62
Washington	200	112	66	6	5	1	20	49	24	14	7	3	507	0.54
Virginia	417	68	4	6	0	0	1	0	3	1	0	0	501	0.53
South Carolina	306	126	5	11	1	0	11	0	3	1	0	0	465	0.49
California	3	83	6	21	1	0	328	4	3	4	2	1	457	0.48
Vermont	248	40	47	2	0	0	1	7	4	2	1	0	353	0.37
Illinois	48	54	19	5	3	1	120	22	22	20	8	2	326	0.34
Connecticut	218	41	24	5	0	0	0	1	9	6	4	1	310	0.33
Iowa	4	56	1	4	5	0	179	17	4	2	1	0	274	0.29
Ohio	62	28	33	4	2	0	80	30	15	7	4	2	270	0.29
Colorado	48	48	117	1	26	3	0	1	1	0	0	0	246	0.26
Oregon	17	129	9	34	2	0	24	18	4	2	1	0	240	0.25
Pennsylvania	168	19	17	3	0	0	0	2	2	1	1	0	214	0.23
Montana	34	77	57	3	15	0	7	13	1	0	0	0	207	0.22
Idaho	32	108	14	2	2	0	8	3	1	0	0	0	169	0.18
Delaware	52	80	1	6	0	0	1	0	1	1	0	0	144	0.15
Rhode Island	78	4	7	3	0	0	0	0	2	1	1	0	96	0.10
Wyoming	16	20	50	1	3	0	0	1	0	0	0	0	92	0.10
Nebraska	3	53	0	4	1	0	0	0	0	0	0	0	61	0.06
Hawaii	0	0	0	0	0	8	9	1	2	0	22	4	47	0.05
Utah	4	5	19	0	2	2	1	2	0	0	0	0	37	0.04
Texas	12	13	0	0	0	0	0	0	0	0	0	0	25	0.03
North Dakota	3	14	0	2	2	0	0	1	0	0	0	0	23	0.02
West Virginia	1	2	0	0	0	0	0	0	0	0	0	0	3.5	0.004
Nevada	0	1	0	0	0	0	0	1	0	0	0	0	2.4	0.003
South Dakota	0	2	0	0	0	0	0	0	0	0	0	0	2.1	0.002
Arizona	1	0	0	0	0	0	0	0	0	0	0	0	2.0	0.002
New Mexico	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.000
Total area	56,179	24,026	4025	1311	226	57	5717	1177	1004	602	338	88	94,750	100
% tot. area	59.3	25.4	4.2	1.4	0.2	0.1	6.0	1.2	1.1	0.6	0.4	0.1	100	

includes 4017 km^2 of histosols and 484 km^2 of HEs. Ten states harboring most (93 %) of this category for histosols and HEs combined are, in descending order, Minnesota, Florida, North Carolina, Michigan, New Jersey, Wisconsin, Louisiana, Indiana, New York, and South Carolina (Fig. 2a and b, Table S5 and S6).

Of the top ten states with the largest percentage of the total mapped peatlands under agriculture, seven were in the Midwest (Minnesota, Wisconsin, Michigan, Indiana, Iowa, Illinois, Ohio), two were in the Southeast (Florida, North Carolina) and one was in the West (California) (Fig. 1, Table 1, Table S3). In the Upper Midwest (Minnesota, Wisconsin, Michigan), the fraction of national peatland area was high and paralleled by the fraction of total agriculture on peatlands, whereas in the Lower Midwest (Iowa, Illinois, Indiana, Ohio) these states harbor a lower fraction of the total peatland area, but a much higher fraction of agriculture on peatlands (Figs. 1 and 2, Table 1, Table S3).

Of the 6392 km^2 of histosols under agriculture (from the NASS data), almost half (47.1 %) was >150 m from linear features (ditches, roads, railroads), 13.2 % was within 150 m of roads, 31.1 % within 150 m of ditches, and 7.3 % within 150 m of both ditches and roads (Fig. 2a–Table S6). Similar patterns were observed for HEs (Fig. 2b–Table S7). Note that even where no surface ditches were mapped, the vast majority of peatlands under agriculture as practiced in the US are likely drained by subsurface drainage tiles used to lower water tables (Valayamkunnath et al., 2020) and so are treated as drained for emissions estimation purposes (see section 3.4).

3.3. NRCS easements and protected status

Of the lands mapped as histosols and HEs, 635 km^2 of histosols and 81 km^2 of HEs were in NRCS wetland easements, equal to 9.9 % and 6.2 % of total histosols and HEs mapped under agriculture (NASS estimate), respectively (Table S8, Fig. 3). Five states together have almost 70 % of the national area of conservation easements containing histosols plus HEs (in descending order): Florida, North Carolina, Wisconsin,

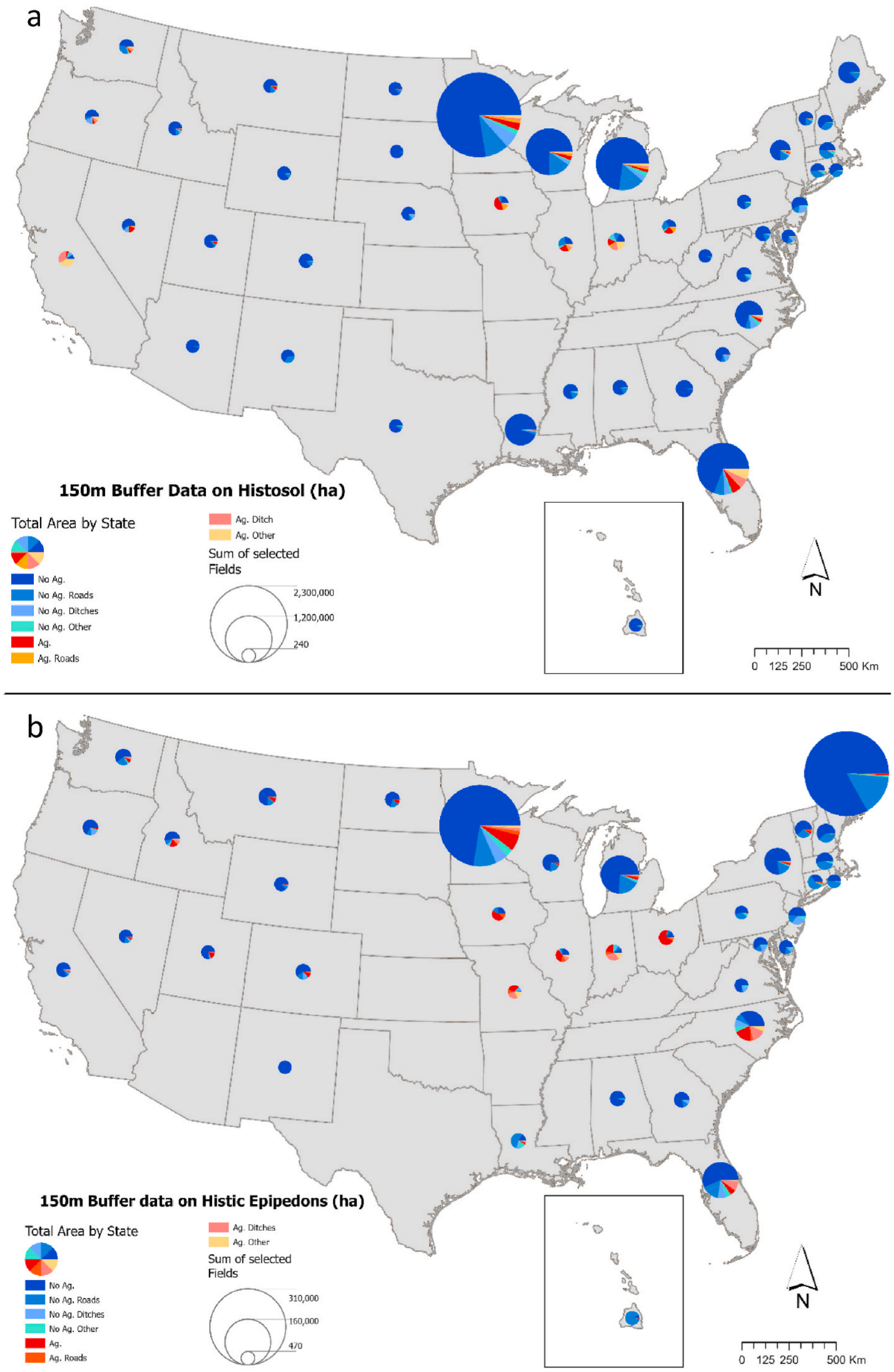

Fig. 2. Map showing, for each US state, a pie chart containing the proportion of mapped histosols a) and histic epipedons b) that intersect with major land use classes (presence/absence of agriculture) and linear disturbances (ditches, roads, and railroads) by state. Area of the pies scales non-linearly with the area of the peatlands in that state.

Minnesota, and Michigan (Fig. 3, Fig. S2; Table S7).

Of the total mapped histosols, 38 % were in one of the two most protected classes in the PAD-US (Table 2). As an indicator of the effect of this on land use, GAP status 1–3 were mapped as having a very low percent agriculture, with a higher percentage (5.6 %) in the least protected class (GAP 4). Lands not in the PAD-US harbor 17 % of histosols. Of this 17 %, about 27 % (NLCD-estimate) were under agriculture (Table 2).

3.4. Emissions

Using Tier 1 emission factors, we mapped estimated emission reductions (Fig. 4, Fig. S3) and conservatively estimated the potential reduction by complete hydrologic restoration of the drained histosols and HEs at approximately 36.8 Tg CO_2-e yr^{-1} (Table 3). Of this, about 74.5 % (23.6 Tg from histosols and 4.1 Tg from HEs) is associated with agricultural land use, whereas about 25.5 % (8.0 Tg from histosols and 1.2 Tg from HEs) is associated with non-agricultural land uses. Potential ER for restoration via ditch plugging was estimated at 92.5–102 % relative to peatlands restored by ditch filling. [see Supplementary

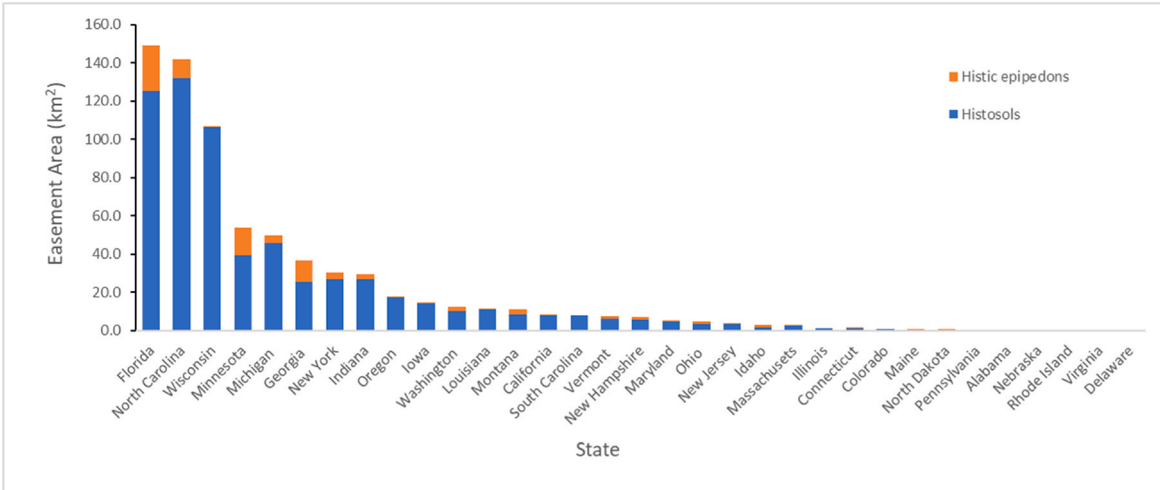

Fig. 3. A graph of the area, in km^2, of histosols and histic epipedons contained in Natural Resources Conservation wetland easements in CONUS + Hawaii, with states ordered from greatest to least area of combined histosols and HEs.

Table 2
Histosols by protected area status in the US Protected Area Database (PAD-US), and the percentage mapped as under agriculture, for CONUS + HI, as derived from intersection with the National Land Cover Database (NLCD).

GAP status	Non-Agricultural (km^2)	Agricultural (km^2)	Total (km^2)	% Agricultural
1	16,505	134	16,639	0.8
2	19,174	229	19,403	1.2
3	3551	2	3553	0.1
4	36,835	2194	39,029	5.6
Total in PAD-US	76,065	2559	78,624	3.3
Not in PADUS (NLCD)	11,791	4335	16,126	26.9
Total histosol (NLCD)	87,856	6894	94,750	7.3

Methods, Table S9]. The ten states estimated to have the highest potential emission reductions were (in descending order) Florida, Minnesota, North Carolina, Michigan, Wisconsin, Indiana, California, New Jersey, Iowa, and New York, together totaling 92 % (Fig. 4, Table 3). Note this does not consider peat mining, which is a relatively small emissions source in the US that is quantified in the US GHG inventory (EPA, 2023).

4. Discussion

To our knowledge, this is the first US national map to assess the condition of peatlands. Our findings suggest substantial opportunities for peatland restoration in many parts of the US. The areas with the most degraded peatlands tend to be agricultural areas at the margins of major extensive regions of peatlands, for example western and southern Minnesota, and the southern portions of the Midwest. These regions tend to have smaller isolated pockets of highly altered peatlands embedded in an agricultural matrix. States with larger contiguous areas of degraded peatlands include Florida, dominated by agriculture in the Everglades Agricultural Area (Aich et al., 2013), and California, dominated by agriculture in the Sacramento Delta (e.g., Knox et al., 2014). The feasibility of restoring peatlands depends on a large number of factors, including nature of the degradation, access, ownership, local laws and regulations, potential offsite impacts such as flooding, cost, co-benefits, tradeoffs, and site characteristics such as topography, hydrology, current vegetation, and the availability of ditch filling material (Artz et al., 2018, Convention on Wetlands, 2021). For example, in the case of

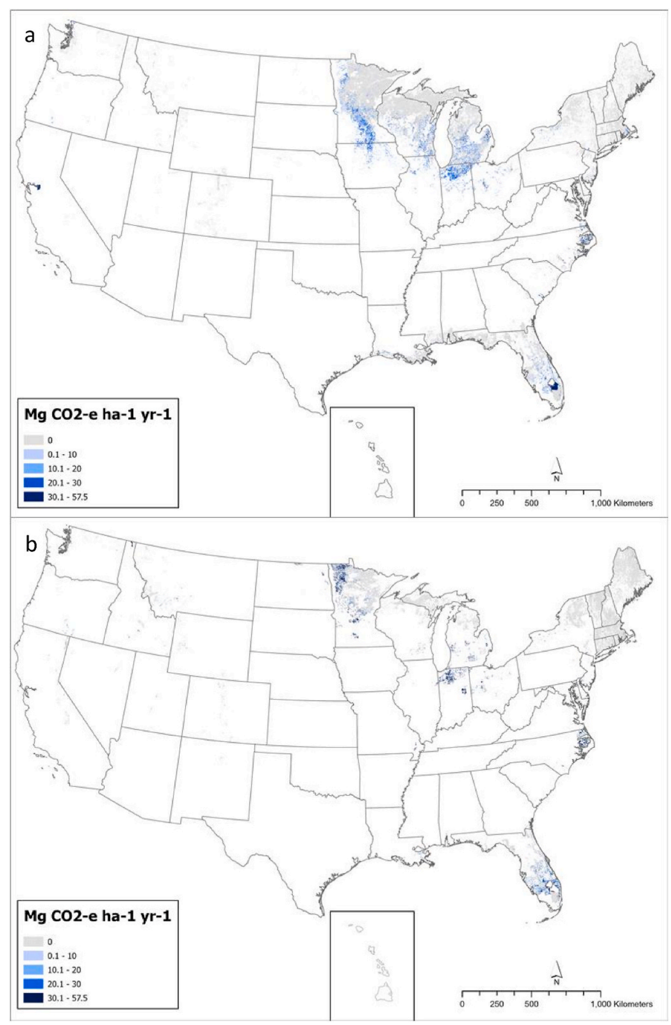

Fig. 4. Potential emission reductions for rewetting of drained a) histosols and b) histic epipedons in CONUS + Hawaii. Mapped data represent the reductions in tonnes CO_2 equivalents ha^{-1} yr^{-1} for CO_2, CH_4, N_2O, and DOC.

Table 3
Total emission reductions estimates for rewetting of drained histosols and histic epipedons (HE) separately for agricultural (Ag) and ditched non-agricultural (Non-Ag) land uses, for the combined effect of changes in emissions of CO_2, CH_4, N_2O and DOC, all expressed as tonnes CO_2-e yr^{-1}. See Table S9 for more details on specific EFs used. Missing states have no histosols mapped.

State	Ag-HE	Non-Ag-HE	Total HE	Ag-Histosol	Non-Ag-Histosol	Total Histosol	Total HE + Histosol
Florida	723,016	273,360	996,376	10,075,780	1,554,218	11,629,997	12,626,373
Minnesota	871,331	338,385	1,209,715	3,333,997	2,279,359	5,613,357	6,823,072
North Carolina	1,478,714	182,235	1,660,949	1,582,017	1,329,812	2,911,829	4,572,778
Michigan	159,402	14,565	173,967	1,856,087	343,914	2,200,001	2,373,968
Wisconsin	22,752	530	23,282	1,793,620	489,488	2,283,108	2,306,390
Indiana	307,419	11,199	318,619	1,662,140	117,480	1,779,620	2,098,239
California	5445	5925	11,371	1,344,733	130,281	1,475,014	1,486,385
New Jersey	8797	139,669	148,466	20,062	549,398	569,460	717,926
Iowa	4550	0	4550	551,779	6581	558,361	562,911
New York	74,228	9582	83,810	270,579	129,069	399,648	483,458
Louisiana	8398	41,835	50,232	27,787	387,776	415,563	465,795
Ohio	180,953	285	181,238	248,850	4688	253,538	434,776
Illinois	25,777	103	25,879	371,697	6123	377,820	403,699
South Carolina	0	0	0	45,036	163,279	208,316	208,316
Oregon	2681	32,826	35,507	93,614	63,040	156,654	192,161
Washington	28,954	8296	37,249	96,643	36,461	133,104	170,353
Massachusetts	2204	4965	7169	108,851	50,043	158,894	166,063
Idaho	89,153	5781	94,933	24,565	16,851	41,417	136,350
Maryland	1711	24,932	26,643	8167	71,592	79,759	106,402
Virginia	83	12,574	12,657	3879	74,463	78,343	90,999
Delaware	1170	11,529	12,699	5847	45,756	51,603	64,302
Georgia	0	20,253	20,253	8860	16,487	25,347	45,600
Montana	11,041	2023	13,065	21,732	7129	28,861	41,925
Connecticut	2240	751	2992	997	30,794	31,791	34,783
Mississippi	0	0	0	2392	28,346	30,738	30,738
Colorado	4832	16,810	21,642	258	5223	5482	27,124
Maine	20,002	275	20,277	4308	1902	6210	26,487
Hawaii	5584	14,387	19,971	429	1341	1769	21,741
Vermont	2674	1521	4194	3258	11,401	14,659	18,853
Nebraska	0	0	0	1367	15,844	17,210	17,210
Missouri	17,130	0	17,130	0	0	0	17,130
North Dakota	14,523	0	14,523	340	182	522	15,045
Utah	3928	709	4637	4333	739	5072	9710
Alabama	0	811	811	4094	4249	8342	9153
Pennsylvania	0	295	295	1571	2025	3596	3891
Wyoming	864	1000	1863	229	1554	1783	3646
Rhode Island	63	98	161	386	1600	1986	2147
Nevada	516	887	1403	99	550	649	2053
N. Hampshire	172	74	247	160	1367	1527	1774
Texas	0	0	0	4	1562	1566	1566
Arizona	0	0	0	0	0	0	0
New Mexico	0	0	0	0	0	0	0
South Dakota	0	0	0	0	0	0	0
West Virginia	0	0	0	0	0	0	0
Total	4,080,306	1,178,470	5,258,776	23,580,548	7,981,967	31,562,515	36,821,291

agricultural lands, there is a lot of investment to make these lands agriculturally productive via drainage. Due to these investments in this infrastructure, many do not voluntarily apply for the ACEP-WRE program to restore these lands, and the cost to move these lands into any restoration program could be high.

4.1. Peatland protections

When analyzing the protections afforded to histosols in CONUS, the negative relationship between protection level and agricultural land uses is evident. A large proportion (38 %) of the mapped histosols fall under PAD-US classes generally considered protected (GAP status 1 or 2), and the mapped agricultural land uses in those areas amounts to only 1 % on an area basis. Interestingly, areas in GAP status 3 had proportionally less agricultural land use (0.1 %) than the ostensibly more protected areas. GAP status 3 areas are nominally protected but may permit extractive uses such as mining and forestry. In the context of agriculture on histosols, this may not produce a distinction in practice, explaining why agricultural use of histosols in GAP status 3 is similar to that of histosols in GAP status 1 or 2. GAP status 4 lands are classified when there is no stated protection from conversion or use. Unsurprisingly, the agricultural use of histosols in this protection class figures higher than any of the other GAP classes, but lower than lands not included in PAD-US, implying that inclusion in even the least protected PAD-US class is associated with less agricultural conversion.

One of the novel findings from our analysis is the area of peatland histosols in NRCS easements. Historically, this program has not targeted enrollment based on GHG reductions from histosol restoration. Since the easement program has not specifically focused on restoration of peatland hydrology for climate mitigation purposes, it is likely that additional guidance on how to restore agroecosystems on histosols to provide stable high water tables, if implemented, would result in reduced GHG (especially CO_2 and N_2O) emissions. Note that individual states are also pursuing programs to incentivize peatland restoration, e.g., the state of Minnesota Reinvest in Minnesota (RIM) program (https://bwsr.state.mn.us/reinvest-minnesota-overview). These wetland management programs can use our maps for an initial assessment of the area of peatlands that can be restored as part of their programs. We recommend that estimates be updated with any additional state level data or improved maps.

4.2. Implications of findings for Natural Climate Solutions

This study makes clear that the US harbors significant areas of peatland that are under pressure from a variety of factors, most notably agricultural conversion, ditching, and roads. Of these, conversion and use for agriculture has the highest emissions, and explains the fact that of the top ten states for emissions, several have a relatively small total peatland area, but a high rate of agricultural peatland conversion. Most peatland soils converted to agriculture will be subject to subsurface tile drainage, which is typically laid at high density, meaning that entire agricultural fields will be subject to lowered water tables (Valayamkunnath et al., 2020). Drainage and fertilization of peat soils leads to elevated emissions of N_2O (Lin et al., 2022), which has a global warming potential (GWP_{100}) approximately 265 times higher than CO_2 (Myhre et al., 2013). The combination of high peat oxidation to CO_2 and elevated N_2O emissions makes these ecosystems very potent drivers of global warming and a target for restoration if the goal is climate change mitigation.

However, the cost per unit area of restoring these peatlands is likely to be high, because of the value of the land for agriculture and the challenges of restoration in an agricultural matrix. There are a number of proposed approaches for mitigation of emissions from these lands (Liu et al., 2020; Freeman et al., 2022; Lin et al., 2022). Although the restoration of drained peatlands that are not under agriculture are likely to provide less emission reduction per unit area, the costs for restoration are often lower given their lower land values and the potential for simpler restoration approaches. A number of government agencies (e.g., NRCS, Minnesota Department of Natural Resources, Minnesota Board of Water and Soil Resources) and non-governmental organizations (e.g., The Nature Conservancy) have restoration programs that target both agricultural and non-agricultural wetlands, including peatlands.

The default emission reductions we estimate in the map should be taken as rough estimates to aid in project prioritization, and would not in themselves be the basis for a credible estimate of actual emission reductions at any one site, e.g., for use in carbon markets. The emission factors used as the basis for emission reduction estimates are the default Tier 1 emission factors from the IPCC 2013 report, and, as such, represent a starting point that can be used as the simplest approach for reporting emissions from different land uses on peatlands. These emission factors can be refined by higher tier estimation using local knowledge derived from system specific emission quantification or locally parameterized models.

4.3. Comparison with other emissions estimates

The total potential emission reductions estimated in the present study (36.8 Tg CO_2-e yr^{-1}) should be considered a rough estimate, given the lower tier EFs used and data gaps. For context, this represents approximately 0.6 % of US total estimated emissions of GHG (in 100 year CO_2 equivalents) for 2019 (EPA, 2024). Our estimate of emission reductions if all lands were restored is about 4x higher than the 9 Tg CO_2-e yr^{-1}estimate in Fargione et al. (2018), who used a different approach to estimating area of degraded peatlands, GHG emissions, and potential emission reductions. Without a full comparison of our two approaches, it is difficult to say what led to the large disparity.

Although our primary goal was to provide a resource for prioritization of restoration benefits at various spatial scales by estimating ERs, and not GHG accounting, as a check on our findings we can compare our net emissions (not ERs, as EPA does not calculate those) estimates with those of the National Greenhouse Gas Inventory (EPA, 2023) for emissions from organic soils. We used tier 1 EFs from the IPCC 2013 Wetlands supplement (IPCC, 2014), whereas EPA 2023 used a combination of tier 3, tier 2, and tier 1 EFs from the IPCC 2006 Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) as needed. Another difference in methodology between the EPA inventory and our estimate is the handling of histosols under developed lands. In EPA 2023, these lands "are assumed to be losing C at a rate similar to croplands due to deep drainage," whereas we conservatively attribute drained EFs to developed lands (*per* NLCD) only when they fall within our mapped ditch buffer zones, using undrained grassland EFs for all other developed lands. For the most directly comparable estimates, the GHG Inventory emissions attributed to cropland histosols totaled 35.8 Tg CO_2-e for 2021, while our estimate was 29.6 Tg CO_2-e (17.9 % lower). Hence our agricultural emission estimates are conservative compared to the GHG Inventory, but reasonable for ranking of restoration projects as to their likely magnitude of emissions prior to rewetting.

4.4. Limitations of the data

4.4.1. Data gaps

As pointed out in the methods, there are regions of the US with gaps in the gSSURGO data layer, some of which are being filled. Additionally, in certain regions we have been applying other mapping approaches to areas not covered by gSSURGO data, e.g., in National Forests in the Rocky Mountains we have been applying remote-sensing based mapping methods developed to map mountain peatlands (Chimner et al., 2019).

4.4.2. Data quality

Soil survey data are subject to data quality issues related to a variety of factors. One of the most obvious is variation in consistency across map units that are evident as artifacts, e.g., at county boundaries (e.g., Miller, 2012). There are also isolated examples of regions where histosols have been undersampled, e.g., in the Canaan Valley region of West Virginia (Elizabeth Byers, personal communication; Fig. S4).

Similarly, NLCD and NASS data are subject to error in attribution (Wickham et al., 2023). In particular, land cover attributable to agriculture (cropping, hay, or pasture) can be hard to distinguish from land restored to natural land cover, e.g., fen vegetation dominated by graminoids on sites formerly cropped (Sara Thompson, personal communication). Errors in this category can be observed in our dataset, so users should validate land use on potential sites via high resolution longitudinal imagery and site visits.

Additionally, because some polygons contain spatially unresolved mixtures of organic and mineral soils, we have mapped the peatlands as a percentage for the whole rasterized polygon. This reduces the spatial specificity of the map for these pixels, especially those with lower percentages of histosols. Hence, field validation of peatland extent and condition is essential as a phase of project prioritization. For this purpose, we recommend probing soils at replicate locations in the project area to a depth of at least 40 cm (and up to 80 cm if interbedding of mineral layers are present) and analyzing soils for organic matter or C content to match the definition of histosols or histic epipedons (Soil Survey Staff, 1999).

Last, the NHD ditch layer does not capture all ditches in peatlands. Personal observation by authors and colleagues points to numerous ditches evident in remote sensing that for various reasons have not been captured during layer generation, e.g., in the Hiawatha National Forest, Michigan, and in Taylor County, Florida. For this reason, careful examination of remote imagery and site visits to determine current ditch status of any project sites should be carried out early in any project evaluation process.

4.5. Shallow peat

The US definition of peatlands is congruent with hydric histosols, which, with a few exceptions, are defined as soils with 40 cm of organic soil in the top 80 cm. This definition requires thicker peat layers than those of many other countries (Lourenco et al., 2023). In addition to histosols, the US soil taxonomy recognizes mineral soils with histic epipedons (Soil Survey Staff, 1999). These are hydric soils that typically have >20 but <40 cm of peat or have been plowed in a way that mixes the organic matter into the mineral soil. To determine whether this is a large potential target for restoration, we calculated the total area of soils mapped with HEs. This area (13,533 km^2) is approx. 14 % of the total area of mapped histosols. Our analysis reveals that these ecosystems are converted to agriculture at approximately the same rate as histosols. However, as these soils often occur in mixed polygons with histosols, it is possible that they are preferentially converted, but our analysis lacks the spatial resolution to detect this.

4.6. Map use cases

Our intention in producing the map was to provide resources that would permit individuals and organizations to explore the potential for peatland restoration at different scales, whether to inform policy or to improve land management/restoration project prioritization. The map will complement restoration guides and decision support tools that are under development. Currently users can use the web version of the map at the PeatRestore website (https://peatlands.mtri.org/) to familiarize themselves with the features of the project, and find other resources, e.g., a recently developed guide to restoration of mountain peatlands (Chimner and Cooper, 2024). Additional resources (restoration guides, decision support tools) will be deposited on the web page as they are developed.

5. Conclusions

Peatlands in the US have experienced regionally varying levels of land use change and degradation of ecosystem services. In particular, peatlands are heavily impacted by agriculture, ditching, and roads. Peatland degradation is concentrated in areas favorable to agriculture, leading to significant GHG emissions. Mitigating those emissions can be accomplished by peatland restoration, which at a minimum requires rewetting (hydrologic restoration). Existing wetland easement programs have included significant areas of histosols, but the impact of those programs on peatland GHG fluxes is at present still uncertain, because the original intent of these efforts was not peatland restoration *per se*. The information provided in our mapping effort can be used as a starting point for identifying areas of high priority for restoration. Currently, the maps in the present study are slated to be complemented by restoration resources as part of the PeatRestore project. With the right guidance and caveats this information can aid users in making decisions about where and how to initiate restoration efforts, or at the state level to evaluate the potential for peatland restoration efforts to contribute to state ecosystem management plans.

CRediT authorship contribution statement

Erik A. Lilleskov: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kevin J. McCullough:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Dominic M. Uhelski:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127100.

Data availability

I have shared the link to the data in the manuscript

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