North American Swamps: What Lies Beneath

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Abstract

Terrestrial wetlands are a highly significant carbon reservoir in North America. Forested wetlands, or swamps, are an important category of North American wetland and include boreal forested peatlands, swamps dominated by needle-leaved trees including Thuja (cedar), Picea (Spruce), Larix (Tamarack) or Taxodium (bald cypress), swamps dominated by broad-leaved trees or shrubs including Fraxinus (Ash), Ulmus (Elm), or Acer (Maple), as well as mangroves. The Second State of the Carbon Cycle Report estimates that forested wetlands may make up ~55% of the total terrestrial wetland area for North America, although estimates vary considerably due to different mapping conventions and classification systems across national and provincial borders, and also due to the ongoing impacts of land use change. Additionally, that report suggests that forested wetlands contain larger total carbon pools than non-forested wetlands, and that forested wetlands effect 53% of the estimated 123 Tg total wetland annual carbon sink for North America. Uncertainties in the sizes of the forested wetland soil carbon pools continue to be significant due in part to insufficient data on variabilities in carbon densities across diverse swamp types. Further, there are limited data on the rates of vertical accretion of swamp soils and the associated long-term rates of carbon accumulation, needed for better predicting impacts of climate warming on carbon sequestration in swamp soils. We present here a comparative synthesis of swamp soil carbon properties including bulk densities, organic carbon contents, soil thicknesses, rates of vertical accretion and rates of long-term carbon accumulation, from >200 swamp sites. We compare these properties for broad-leaf swamps (including mangroves), needle-leaf swamps, mixed swamps, and shrub-dominated swamps, and also compare across North American Ecoregions. The results show significant variability across peat-forming and mineral swamps, and indicate rates of carbon accumulation in some swamp types similar to those of northern bogs and fens.

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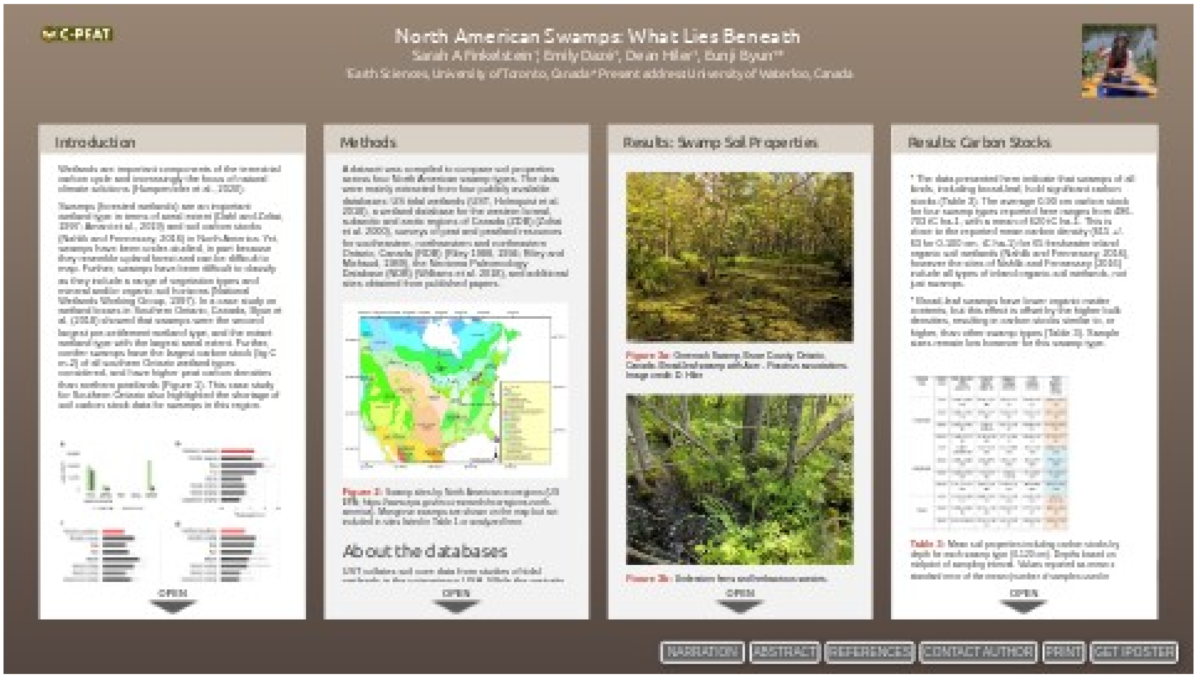

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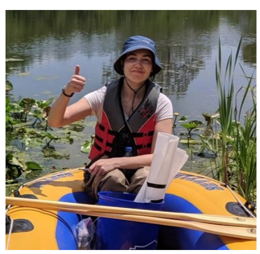

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INTRODUCTION

Wetlands are important components of the terrestrial carbon cycle and increasingly the focus of natural climate solutions (Humpenöder et al., 2020).

Swamps (forested wetlands) are an important wetland type in terms of areal extent (Dahl and Zoltai, 1997; Amani et al., 2019) and soil carbon stocks (Nahlik and Fennessey, 2016) in North America. Yet, swamps have been under-studied, in part because they resemble upland forest and can be difficult to map. Further, swamps have been difficult to classify as they include a range of vegetation types and mineral and/or organic soil horizons (National Wetlands Working Group, 1997). In a case study on wetland losses in Southern Ontario, Canada, Byun et al. (2018) showed that swamps were the second largest pre-settlement wetland type, and the extant wetland type with the largest areal extent. Further, conifer swamps have the largest carbon stock (kg C m-2) of all southern Ontario wetland types considered, and have higher peat carbon densities than northern peatlands (Figure 1). This case study for Southern Ontario also highlighted the shortage of soil carbon stock data for swamps in this region.

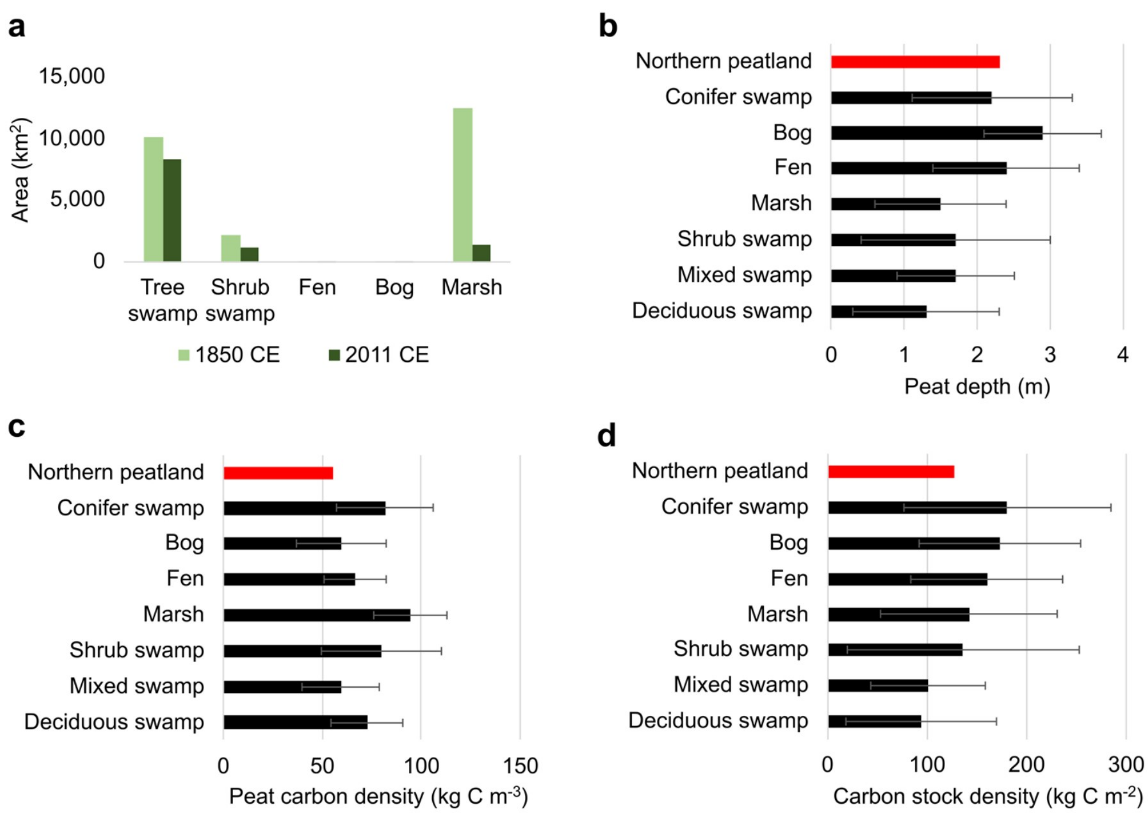

Figure 1: Southern Ontario wetlands (Byun et al. 2018) in comparison with northern peatlands (>45°N) (Loisel et al. 2014); a) estimated wetland area for pre- and post- settlement southern Ontario; b) average peat depths for southern Ontario wetland types in comparison to the 2.3-m mean for northern peatlands (Gorham 1991, Loisel et al 2014); c) Southern Ontario wetland peat carbon density = carbon (%C) * peat bulk density (g/cm3) * 1000 (kg/g * cm3/m3) (Table 2.3 of Byun et al 2018) and northern peatland mean (0.47 * 0.118 * 1000 = 55.46) (Loisel et al. 2014); d) wetland carbon stock density = peat carbon density (kg C/m3) * peat depth (m) (Table 2.4 of Byun et al., 2018) and northern peatland mean (55.46 * 2.3) (Loisel et al. 2014).

Because of these data gaps and the ambiguities in terms of classification, swamps are often missing from or difficult to integrate into national mapping schemes and peatland carbon models (Bona et al., 2020; Webster et al., 2018).

Our goal here is to build on previous results established by Byun et al. (2018) for Southern Ontario by extending to a wider region. Here, we collate soil carbon data from four different North American swamp types (broad-leaf, needle-leaf, mixed and shrub/thicket) with the aims of (i) evaluating differences between them in terms of soil properties and carbon stocks, (ii) highlighting the significance of swamps from a soil carbon perspective, and (iii) showing data gaps.

METHODS

A dataset was compiled to compare soil properties across four North American swamp types. The data were mainly extracted from four publicly available databases: US tidal wetlands (UST, Holmquist et al. 2018), a wetland database for the western boreal, subarctic and arctic regions of Canada (ZDB) (Zoltai et al. 2000), surveys of peat and peatland resources for southeastern, northwestern and northeastern Ontario, Canada (RDB) (Riley 1988, 1994; Riley and Michaud, 1989), the Neotoma Paleoecology Database (NDB) (Williams et al. 2018), and additional sites obtained from published papers.

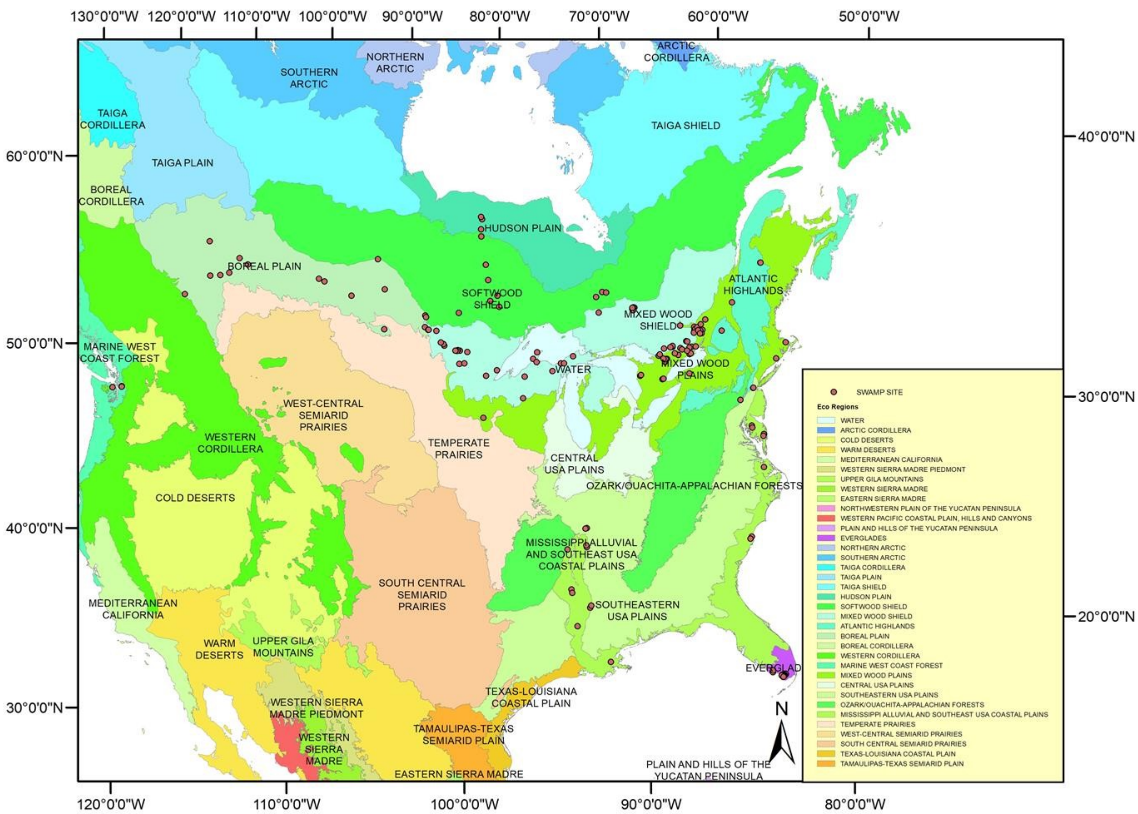

Figure 2: Swamp sites by North American ecoregions (US EPA; https://www.epa.gov/eco-research/ecoregions-north-america). Mangrove swamps are shown on the map but not included in sites listed in Table 1 or analyzed here.

About the databases

UST collates soil core data from studies of tidal wetlands in the coterminous USA. While the majority of UST sites are non-forested marshes, 34 were dominated by forested biomass and retained here as swamps. The original studies were used to assign sites to broad-leaf, needle-leaf, mixed or shrub/thicket swamp types.

ZDB specifies 33 types of wetland, of which five are named as types of “swamp”. A total of 21 sites in ZDB were designated as “swamps”. The category “Broad-leaf swamp” was assigned to swamp sites that had >10% canopy cover by broad-leaf trees and <10% needle-leaf and vice versa for needle-leaf swamp. Mixed swamp was assigned to sites that had >5% of both needle and broad-leaf species. Sites with <10% tree cover but >10% shrub cover were classified as shrub swamp. Additionally, a sub-set (N = 75) of sites not named as “swamps” in ZDB but classified as “forested fens” or “forested bogs” were included for comparison.

RDB (Riley 1988, 1994; Riley and Michaud, 1989) contains data from peatlands in Ontario, Canada. Sites were extracted from RDB using the following categories that existed within the RDB: conifer swamp, mixed swamp, thicket swamp, hardwood (equivalent to broad-leaf) swamp.

NDB is a paleoecological database (https://www.neotomadb.org/) (https://www.neotomadb.org/)containing records from many depositional environments, including wetlands. To identify NDB sites corresponding to swamps or forested wetlands, the "advanced" search menu was used with the following settings: "collection type" was set to "core" to isolate studies that focused on soil; "deposit" was set to include "swamp", "tidal freshwater forested wetland", "slough", "small hollow > vernal pool" and "mangrove". Further, all sites with site names containing any of the following terms were checked: "swamp", "forested wetland", "slough", "forested hollow", "forested pool", "vernal pool", "forested peatland", "mangrove", "wooded pond", "pocosin", and "carr". The 44 sites returned using these criteria were then screened for available data on swamp soil carbon, and 17 were retained.

Database	# Sites	# Cores	Reference
US Tidal Wetlands (UST), Forested wetlands (freshwater)	8	8	Holmquist *et al.* (2018)
Zoltai (ZDB), Swamps	21	21	Zoltai *et al.* (2000)
Riley (RDB)	82	82	Riley (1994, 1988); Riley and Michaud (1989)
Neotoma (NDB)	17	31	Williams *et al.* (2018)
Other	25	39	
Total number of swamp records included	**153**	**181**	
Zoltai (ZDB), Treed wetlands not named swamps		75*	Zoltai *et al.* 2000

Table 1: Summary of data sources for comparisons of soil properties by swamp type. * These are a sub-set of the non-swamp treed wetlands included in ZDB.

Data analysis

All sites included in the dataset for comparison included at least two of: dry bulk density (BD, g cm-3), organic matter (OM) or organic carbon (OC) contents (g/g, %), and depth (cm). Some included radioisotope dating to permit calculation of accretion rates (cm yr-1) and rates of carbon accumulation (g C m-2 yr-1), following Chambers et al., (2010). We report mean BD, and mean OM/OC for the swamp peat section of each core. These core means were then taken to compute means for each of the four swamp types. Because of the uncertainties associated with defining the boundaries of swamp peat within cores without consistent macrofossil or other paleoecological analyses, we also report mean values by depth, 0-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm, for each swamp type, after Nahlik and Fennessey (2016). Carbon stocks were calculated for depth each section by multiplying mean organic carbon densities (g C cm-3) by depth intervals (cm), and converting to the standard unit of t ha-1 (Howard et al., 2014). Carbon densities are defined as the product of BD (g cm-3) and organic carbon content (g/g).

RESULTS: SWAMP SOIL PROPERTIES

Figure 3a: Greenock Swamp, Bruce County, Ontario, Canada. Broad-leaf swamp with *Acer* - *Fraxinus* associations. Image credit: D. Hiler

Figure 3b: Understory ferns and herbaceous species, Greenock Swamp. Image credit: D. Hiler

* Broad-leaf (BL) swamps were often characterized by *Acer* spp. - *Fraxinus* spp. associations; Needle-leaf (NL) swamps were characterized by *Chamaecyparis thyoides, Thuja occidentalis, Picea mariana, Larix laricina* or *Taxodium distichum*, as typical dominants; mixed (MX) swamps combined both broad-leaf and needle-leaf taxa; shrub/thicket (ST) swamps were characterized by *Alnus, Cephalanthus, Cornus* or *Salix* as typical dominant shrubs. See Dahl and Zoltai (1997) for further details on swamp types.

* A total of 171 cores were included in the data synthesis. Needle-leaf swamps were most abundant in the dataset (110 cores from 82 sites), followed by broad-leaf swamps (24 cores from 18 sites), mixed swamps (20 cores/sites) and shrub swamps (17 cores/sites) (Table 2)

Swamp type	Total Number of cores	Peat depth (cm)	Bulk dens. (g cm^{-3})	OM (%)	OC (%)	Vertical accretion (cm yr^{-1})	aCAR (g m^{-2} yr^{-1})
Broad-leaf	24	101 ± 112 (24)	0.246 ± 0.180 (24)	73.2 ± 18.3 (20)	42.9 ± 8.71 (6)	0.00683 ± 0.00133 (3)	-
Needle-leaf	110	187 ± 135 (110)	0.155 ± 0.0564 (90)	86.07 ± 8.23 (95)	46.7 ± 3.67 (30)	0.0431 ± 0.0309 (39)	44.9 ± 44.8 (31)
Mixed	20	236 ± 186 (20)	0.136 ± 0.0256 (12)	90.0 ± 4.80 (12)	47.6 ± 4.19 (11)	0.0366 ± 0.0290 (8)	-
Shrub	17	180 ± 103 (17)	0.156 ± 0.0437 (16)	88.6 ± 4.84 (16)	44.7 ± 10.1 (14)	-	-

Table 2: Means of soil properties by swamp type. OM = organic matter OC = organic carbon; aCAR = apparent rate of carbon accumulation. Means calculated based on peat section of soil profile. Values reported as mean ± standard deviation (number of samples used in calculation).

* All swamp types have significant carbon densities, reflecting high organic matter contents and bulk densities somewhat higher than northern peatland bogs and fens.

* Comparisons by ANOVA and post-hoc Tukey tests indicate that broad-leaf swamps have significantly higher bulk densities than the other swamp types ($F = 12.9$, $df = 4$, $p<<0.01$) and lower organic matter contents ($F = 13.6$, $df = 4$, $p <<0.01$) (Figure 3), possibly reflecting more labile leaf litter under broad-leaf tree canopies, and/or the hydrological setting of hardwood swamps which is often characterized by seasonal inundation.

* Needle-leaf swamps have the highest rates of peat vertical accretion and available data suggest peat carbon accumulation rates in these swamps approximately double those of northern peatlands. These high rates reflect acidic leaf litter, recalcitrance of needle leaves, associated plants that promote peat accumulation, including Sphagnum mosses.

* Rates of peat vertical accretion in needle-leaf and mixed swamps (0.03 – 0.04 cm yr-1,Table 2) are similar to typical values from northern bogs or fens (e.g., Bysouth and Finkelstein, 2020). Peat vertical accretion is an order of magnitude lower in broad-leaf swamps, and peat depths are also lowest in broad-leaf swamps (Table 2), likely reflecting more pronounced seasonal variability in water table position and more frequent aeration of surface peat.

* Mixed and needle-leaf swamps are similar in terms of soil properties, but mixed swamps are less abundant in the dataset. The criteria used to distinguish between "mixed" and "needle-leaf" swamp vary, and some classifications refer to "mixed hardwood" (ie., Dahl and Zoltai 1997). Inconsistencies in criteria used to define these swamp types could relate to the similarity between these two categories in terms of soil properties.

* Shrub dominated swamps had lower peat depths than needle-leaf or mixed swamps, and no data were available to calculate accretion rates. Lower above-ground biomass in shrub swamps may cause these differences.

* The non-swamp forested wetlands in the ZDB (consisting of forested fens and bogs), have significantly lower bulk densities (Figure 3; ANOVA $F = 12.9$, $df = 4$, $p<<0.01$) than both broad- and needle-leaf swamps but organic matter contents are not distinct from those of the needle-leaf, mixed or shrub swamps. These finding support the idea that nuanced classification systems are required to distinguish swamps from forested fens and bogs.

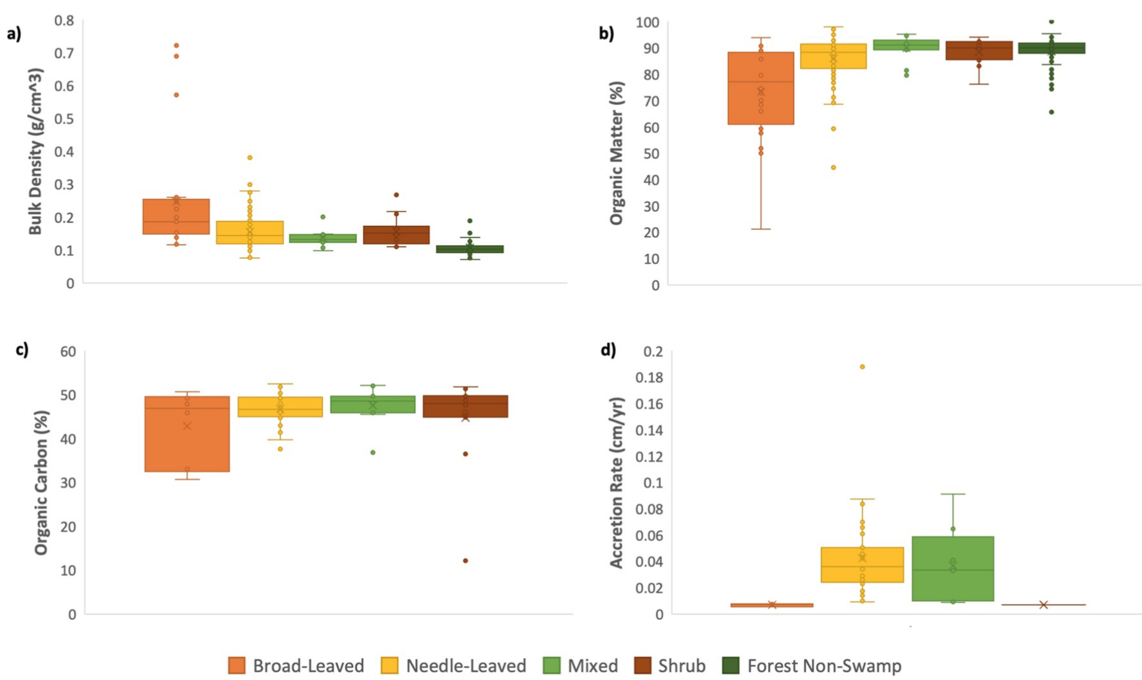

Figure 4: Box and whisker plots of a) bulk density (g cm-3), b) organic carbon content (%), c) organic matter (%) and d) rate of peat accretion (cm yr-1) for the five swamp types as well as forested wetlands not classified as specifically as "swamps" in ZDB. Each point represents the mean value of one soil core.

* For comparison, mangrove swamps in the Everglades (Breithaupt et al., 2017) are most similar to the hardwood swamps

presented here in terms of bulk density and organic matter contents, but have significantly higher rates of sediment accretion (> 0.2 cm yr-1), and fewer sections meeting the definition of "peat".

RESULTS: CARBON STOCKS

* The data presented here indicate that swamps of all kinds, including broad-leaf, hold significant carbon stocks (Table 3). The average 0-90 cm carbon stock for four swamp types reported here ranges from 496-703 tC ha-1, with a mean of 620 tC ha-1. This is close to the reported mean carbon density (615 +/- 63 for 0-100 cm, tC ha-1) for 65 freshwater inland organic soil wetlands (Nahlik and Fennessey, 2016), however the sites of Nahlik and Fennessey (2016) include all types of inland organic-soil wetlands, not just swamps.

* Broad-leaf swamps have lower organic matter contents, but this effect is offset by the higher bulk densities, resulting in carbon stocks similar to, or higher, than other swamp types (Table 3). Sample sizes remain low however for this swamp type.

Swamp Type	Depth (cm)	Bulk density (BD) (g/cm^3)	Organic Matter (OM) (%)	Organic Carbon (OC) (%)	Total Carbon (TC) (%)	Total Carbon Stock (tC/ha)
Broad-leaf	0-30	0.349 ± 0.051 (18)	64.53 ± 5.21 (18)	35.8 ± 4.73 (5)	44.68 ± 1.51 (6)	246.2 ± 35.14 (5)
	30-60	0.635 ± 0.133 (15)	49.67 ± 9.71 (15)	45.95 ± 1.76 (3)	45.02 ± 1.62 (5)	240.1 ± 30.48 (3)
	60-90	0.626 ± 0.205 (9)	52.62 ± 13.65 (9)	49.57 ± 0.01 (3)	49.48 ± 0.02 (4)	217.4 ± 18.52 (3)
	90-120	0.156 ± 0.025 (5)	82.34 ± 6.30 (5)	47.7 ± 2.44 (4)	50.85 ± 2.45 (4)	191.3 ± 23.07 (4)
Needle-leaf	0-30	0.161 ± 0.01096 (58)	84.7 ± 2.10 (65)	44.2 ± 0.772 (21)	43.9 ± 1.28 (38)	178.8 ± 14.96 (25)
	30-60	0.190 ± 0.239 (51)	83.0 ±2.72 (61)	46.9 ± 1.01 (18)	48.3 ± 0.77 (30)	170 ± 9.64 (22)
	60-90	0.230 ± 0.032 (38)	76.6 ± 3.85 (48)	46.89 ± 1.440 (9)	47.9 ± 0.96 (18)	147 ± 15.55 (12)
	90-120	0.181 ± 0.0217 (33)	84.6 ± 2.85 (42)	47.44 ± 1.26 (12)	48.9 ± 0.84 (20)	180.2 ± 13.42 (12)
Mixed	0-30	0.172 ± (0.008 (11)	89.68 ± 0.81 (11)	45.81 ± 0.66 (10)	47.85 ± 0.69 (11)	233.3 ± 26.03 (10)
	30-60	0.153 ± 0.003 (3)	92.13 ± 1.89 (3)	48.73 ± 1.37 (3)	51.17 ± 1.09 (3)	224.3 ± 9.56 (3)
	60-90	0.15 ± 0.006 (4)	87.44 ± 2.16 (4)	43.41 ± 2.62 (4)	46.38 ± 2.84 (4)	196.2 ± 17.26 (4)

Table 3: Mean soil properties including carbon stocks by depth for each swamp type (0-120 cm). Depths based on midpoint of sampling interval. Values reported as mean ± standard error of the mean (number of samples used in calculation). Total carbon stocks (tC ha-1) are calculated for the specified depth intervals (ie. 0-30 cm) only from cores with availability of paired BD and OC measurements. Estimates with larger samples sizes and thus greater confidence are highlighted in blue; estimates with smaller samples sizes and lower confidence are highlighted in orange.

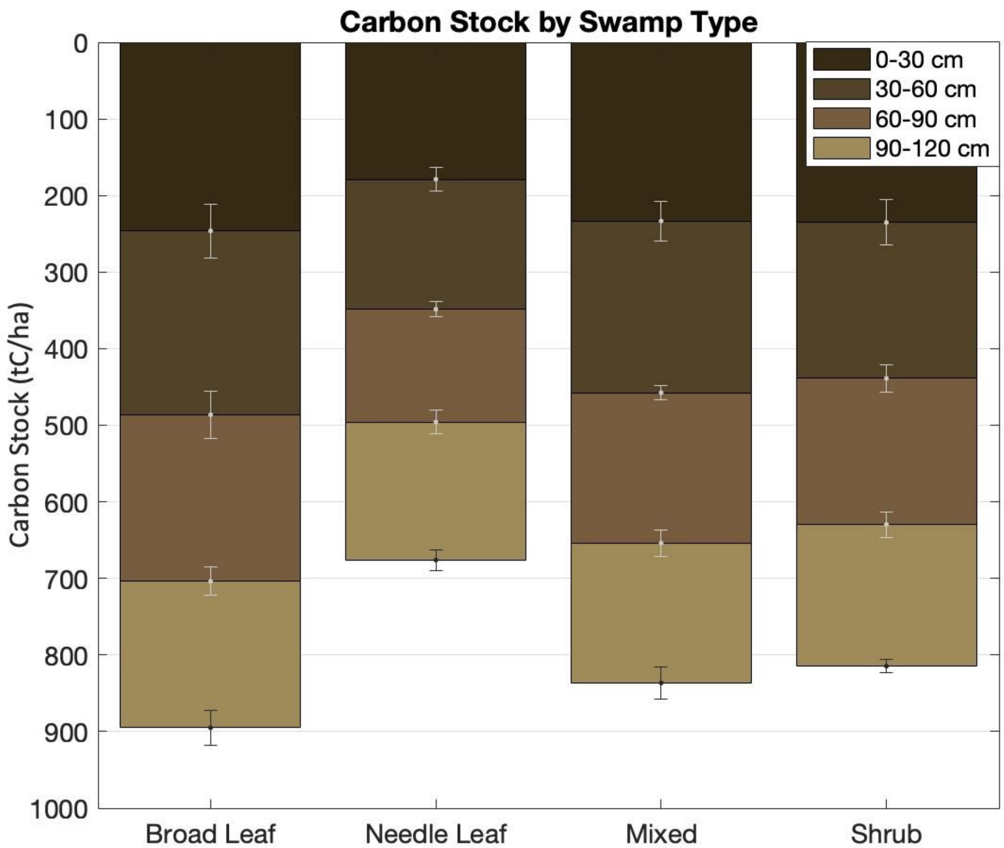

Figure 5: Mean soil carbon stocks to a depth of 120 cm for four swamp types. Sample sizes are shown in Table 3.

Conclusions

These results highlight the importance of swamps as a peat-forming wetland type in North America in terms of carbon densities and carbon stocks. Needle-leaved swamps are better represented in available data. Sample sizes are lower for broad-leaf, mixed, and shrub-dominated swamps. Additional data are needed to improve the comparisons and to test some of the ideas suggested here to explain the differences. Broad-leaf swamps stand out as distinct from the other three categories owing to higher bulk densities and lower peat depths, likely reflecting distinct hydrological and ecological conditions.

Swamps are an important component of wetland soil carbon in North America. The synthesized data provided here can contribute to ongoing efforts to better map and model carbon accumulation in swamps and can help inform land use policies with regard to soil carbon management on lands containing forested wetlands.

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ABSTRACT

Terrestrial wetlands are a highly significant carbon reservoir in North America. Forested wetlands, or swamps, are an important category of North American wetland and include boreal forested peatlands, swamps dominated by needle-leaved trees including *Thuja* (cedar), *Picea* (Spruce), *Larix* (Tamarack) or *Taxodium* (bald cypress), swamps dominated by broad-leaved trees or shrubs including *Fraxinus* (Ash), *Ulmus* (Elm), or *Acer* (Maple), as well as mangroves. The Second State of the Carbon Cycle Report estimates that forested wetlands may make up ~55% of the total terrestrial wetland area for North America, although estimates vary considerably due to different mapping conventions and classification systems across national and provincial borders, and also due to the ongoing impacts of land use change. Additionally, that report suggests that forested wetlands contain larger total carbon pools than non-forested wetlands, and that forested wetlands effect 53% of the estimated 123 Tg total wetland annual carbon sink for North America. Uncertainties in the sizes of the forested wetland soil carbon pools continue to be significant due in part to insufficient data on variabilities in carbon densities across diverse swamp types. Further, there are limited data on the rates of vertical accretion of swamp soils and the associated long-term rates of carbon accumulation, needed for better predicting impacts of climate warming on carbon sequestration in swamp soils. We present here a comparative synthesis of swamp soil carbon properties including bulk densities, organic carbon contents, soil thicknesses, rates of vertical accretion and rates of long-term carbon accumulation, from >200 swamp sites. We compare these properties for broad-leaf swamps (including mangroves), needle-leaf swamps, mixed swamps, and shrub-dominated swamps, and also compare across North American Ecoregions. The results show significant variability across peat-forming and mineral swamps, and indicate rates of carbon accumulation in some swamp types similar to those of northern bogs and fens.

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