A simple field method for estimating the mass of organic carbon stored in undisturbed wetland soils

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SUMMARY

We have compiled a large dataset of peat and soil cores from temperate and boreal regions of eastern Canada to develop a simple field method for estimating the mass of soil organic carbon (SOC) stored in undisturbed wetlands (peatlands, swamps and marshes). We show that it is possible to predict the SOC mass in different wetland types by measuring the organic-rich soil layer thickness in the field. Using this new dataset, we found that SOC mass can be estimated either by using the linear regression equation between peat or soil thickness and SOC mass or by multiplying peat or soil thickness by a mean SOC density. We also show that SOC mass can be estimated by determining the degree of peat humification in the northern peatlands investigated. In this dataset, the precision of estimates is higher for peatlands than mineral wetlands (marshes and swamps), mainly due to the lack of empirical soil core data. The simple approach proposed here could be applied in different wetland regions worldwide where carbon density data from soil cores are available. This cost- and time-efficient method could benefit regional or national-scale carbon inventories.

KEY WORDS: carbon storage, eastern Canada, peat humification, soil cores, soil organic carbon

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INTRODUCTION

Wetlands are among the largest terrestrial carbon reservoirs, and these ecosystems play a crucial role in the global carbon cycle and climate change feedback (Poulter *et al*. 2021). Most wetlands are efficient long-term carbon sinks as large amounts of carbon are accumulated in their soils over centennial to millennial timescales (Mitsch *et al*. 2013, Taillardat *et al*. 2020). Consequently, the alteration or destruction of organic-rich wetland soils by human activities such as drainage can cause irreversible carbon losses. Conservation of wetland carbon stocks is now recognised as one of the most efficient nature-based solutions to mitigate climate change (Drever *et al*. 2021). Estimating the mass of soil organic carbon (SOC) stored in different wetland types is essential for accurately mapping the distribution of terrestrial carbon stocks at the regional or national scales. These data are needed to improve wetland conservation strategies and quantify carbon losses caused by the destruction or alteration of these ecosystems.

Soils are usually the dominant carbon pool in wetlands, especially in peatlands. The SOC mass is usually estimated by measuring organic carbon density along soil or peat cores using laboratory analyses such as loss-on-ignition and elemental C:N ratios (Chambers *et al*. 2011). However, coring entire peat or soil profiles in the field can be logistically challenging. Also, measuring carbon density in the laboratory is time-consuming and expensive, limiting our ability to document the carbon storage function of wetlands, especially in remote regions. The general estimation of soil C stocks in wetlands thus remains limited due to the lack of carbon mass data from various wetland types.

Large-scale national carbon inventories require cost-efficient and rapid methods for estimating the amount of carbon stored in wetlands (IPCC, 2014). This study aimed to develop a simple field method for estimating the soil carbon masses in different wetland types (peatlands, marshes, swamps). To do so, we have synthesised SOC density data from peat and soil cores in temperate and boreal regions of eastern Canada. Using this large dataset, we evaluated whether the SOC mass could be estimated simply by measuring the thickness of the organic-rich soil layer in the field. We tested two estimation approaches, either using the relationship between peat or soil thickness and SOC mass or by

Mires and Peat, Volume 29 (2023), Article 08, 13 pp., http://www.mires-and-peat.net/, ISSN 1819-754X
International Mire Conservation Group and International Peatland Society, DOI: 10.19189/MaP.2022.SNPG.Sc.1818931

multiplying peat or soil thickness by a mean SOC density. For peatlands, considering that peat density increases with decomposition (Silc & Stanek 1977), we also evaluated whether the degree of humification of a peat profile could be used to predict SOC mass.

METHODS

Wetland categories

The wetland categories used to synthesise the SOC data from peat and soil cores (Table 1) broadly follow the Canadian wetland classification system (National Wetlands Working Group, 1997) and are defined mainly according to vegetation composition, shrub and tree coverage, and soil organic layer thickness (≥30 cm = peatlands; <30 cm = marshes and swamps). The criteria for distinguishing the main wetland classes are those used for identifying and mapping wetlands in the province of Québec (Ducks Unlimited Canada & MELCC 2020, Lachance *et al*. 2021). Shallow water wetlands (e.g., ponds <2 m) are not included in this synthesis.

Peatlands include all wetlands with thick organic soils (≥30 cm) containing more than 30 % organic matter by dry weight. The open bog (ombrotrophic peatland) and open fen (minerotrophic peatland) categories correspond to peatlands in which trees (>4 m in height) cover less than 25 % of their surface. Open bogs receive nutrients almost exclusively from precipitation and their plant communities are typically dominated by ericaceous shrubs and *Sphagnum* mosses. Open fens receive nutrient inputs from groundwater and runoff, and are typically dominated by herbaceous plants (Cyperaceae) and brown mosses (e.g., Amblystegiaceae family). Forested peatlands refer to bogs and fens where trees (higher than 4 m) cover more than 25 % of their surface area, including, for instance, black spruce, tamarack, eastern white cedar, and red maple stands.

Swamps include mineral wetlands (organic soil thickness <30 cm) saturated permanently or temporarily and where the woody vegetation (shrub and/or tree) cover is >25 %. In this dataset, coniferous swamps include mostly paludified black spruce forests from boreal regions, where soils are typically covered by a continuous carpet of hypnaceous or *Sphagnum* mosses. Hardwood swamps are more common in the temperate regions, especially along the St. Lawrence River in southern Québec, where forest stands (e.g., *Acer saccharinum*, *Acer rubrum*, *Fraxinus nigra*, *Salix* spp.) are flooded seasonally.

Marshes correspond to permanently or temporarily flooded wetlands connected to open water. They are dominated by herbaceous vegetation

Table 1. Wetland categories in the dataset used for the calculation of SOC densities and SOC masses and their typical vegetation communities.

Wetland classes	Wetland subclasses	Typical non-woody vegetation	Typical woody vegetation
Peatlands	Open bog	*Sphagnum* (e.g., *S. fuscum*, *S. magellanicum*)	Ericaceous shrubs, *Picea mariana*
	Open fen	Cyperaceae, brown mosses (e.g., *Scorpidium* spp., *Straminergon* spp., *Warnstorfia* spp.)	Ericaceous shrubs, *Larix laricina*
	Forested peatland	*Sphagnum* spp., hypnaceous mosses (e.g., *Pleurozium schreberi*)	*Picea mariana*, *Larix laricina*, *Abies balsamea*, *Thuja occidentalis*, *Acer rubrum*, ericaceous shrubs
Swamps	Hardwood swamp	Fern (e.g., *Onoclea sensibilis*), *Equisetum* spp.	*Acer saccharinum*, *Acer rubrum*, *Salix* spp., *Ulmus* spp., *Fraxinus* spp.
	Coniferous swamp	Hypnaceous mosses and *Sphagnum* (e.g., *S. capillifolium*, *S. russowii*)	Ericaceous shrubs, *Picea mariana*, *Abies balsamea*, *Alnus incana* subsp. *rugosa*
Marshes	Freshwater marsh	*Scirpus* spp., *Typha latifolia*, *Sagittaria* spp., *Pontederia cordata*, *Sparganium* spp.	*Alnus incana* subsp. *rugosa*
	Saltwater marsh	*Sporobolus* spp., *Salicornia* spp.	*Myrica gale*, *Spiraea alba* var. *latifolia*

growing on mineral soils, and shrub and tree coverage is <25 %. In this synthesis, marshes are separated between freshwater and saltwater environments, which are characterised by distinct hydrological dynamics and plant species assemblages (Table 1). Water table level variations mainly depend on tides in saltwater marshes and on floods and evapotranspiration changes in freshwater marshes.

Synthesis of organic carbon density data from peat and soil cores

The dataset presented here includes peat and soil cores from non-permafrost wetlands of temperate and boreal regions of eastern Canada (longitudes 80°W – 60°W and latitudes 45°N – 54°N; Figure 1). The wetlands included in this synthesis have not been directly impacted by any major anthropogenic disturbances that could have affected soil density (e.g., drainage, logging). We have synthesised all the available SOC densities from peat and soil cores for the seven subclasses of wetlands (Table 1, Tables S1 and S2 in the Supplement). For saltwater marshes, available SOC density values (n=70) were mostly obtained from a literature review (Table S3). As soil carbon data were lacking for freshwater mineral wetlands, we have collected and analysed new soil cores from hardwood swamps (n=10) and freshwater marshes (n=7) from the St. Lawrence lowlands in southern Québec (Table S1). The methods used to extract cores from peatlands are described in De Vleeschouwer *et al*. (2010), while methods used for coring mineral wetland soils (i.e., marshes and swamps) are presented in Howard *et al*. (2014).

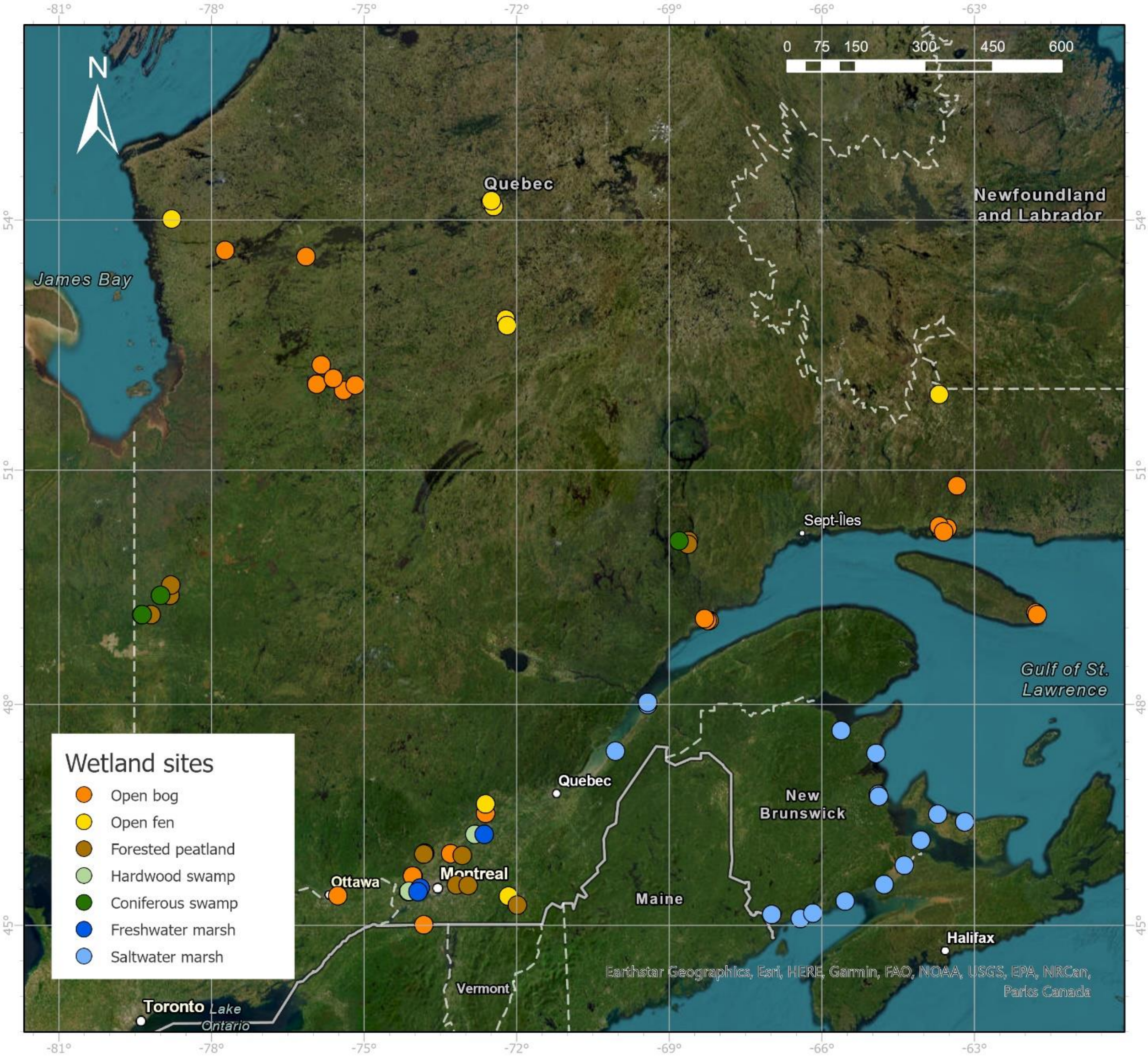

Figure 1. Location of wetlands with SOC density data from peat/soil cores included in the dataset.

Soil organic carbon density measurements

For all the cores included in this dataset, the organic carbon densities were determined from analyses of peat and soil samples in the laboratory following standard procedures (Chambers *et al*. 2011, Howard *et al*. 2014). First, samples of a known volume were dried, and the organic matter (OM) density (g cm^{-3}) was determined from loss-on-ignition (LOI) at 550 °C. For peat samples, the carbon densities were obtained by multiplying the OM densities by 50 % (Turunen *et al.* 2002). For saltwater marsh soil samples, organic matter contents (% LOI) were converted to organic carbon concentrations (% C org) using the equation from Craft *et al*. (1991): % C org = 0.40 × % LOI + 0.0025 (% LOI)^2, and the carbon density was determined by multiplying the % C org by the dry density (g cm^{-3}).

For the new 17 cores collected from freshwater mineral wetlands, the % C org was measured on a subset of 3 cores for hardwood swamps (35 samples) and 3 cores for freshwater marshes (36 samples) using elemental analyses of C:N ratios (Figure 2). For each soil sample, taken at 2-cm intervals along the cores, ~5 mg of homogenised dry subsample was collected. Carbonates were removed using an HCl treatment, and samples were analysed using a Carlo Erba NC 2500 elemental analyser at the Light Stable Isotope Geochemistry Laboratory at GEOTOP-UQAM in Montreal. % C org of all samples from the 17 swamp and freshwater marsh cores (1-cm intervals) were calculated using the linear regression equation of the relationship between % LOI and % C org (Figure 2). Carbon density (g cm^{-3}) was then determined by multiplying the % C org by the dry bulk density (g cm^{-3}).

Peat humification analyses

Following the von Post (1924) method, we visually estimated the degree of humification of samples in three main categories (fibric/mesic/humic) from a subgroup of 22 peat cores included in the dataset. The mean SOC density of each humification class was first calculated for all the peat samples analysed (n=776). Then, a mean SOC density was calculated specifically for the three humification classes for samples from open fens (n=138), open bogs (n=242), and forested peatlands (n=396). For these 22 peat cores, we evaluated whether the degree of peat humification could be used to predict their SOC mass by multiplying total peat thickness by the mean SOC density calculated for the humification class. For estimating SOC mass, we have used the predominant degree of peat humification from the 50–100 cm depth interval, as a previous study showed that samples from these levels best represent the average carbon density from the entire peat profile (Chimner *et al*. 2014). For the shallow peat deposits (<50 cm) the degree of peat humification of the entire profile was used.

Soil organic carbon mass calculation

SOC masses were calculated for the cores in the dataset which included carbon density measurements at a minimum of 2-cm intervals (n=148; Table S4). The SOC mass was calculated by summing all carbon densities measured along each core, with the value expressed in kg m^{-2}. For peatlands, SOC density values (Table S2) were included down to the organic-mineral interface at the base of peat cores, which corresponds to the level where the mineral content of samples, by weight, exceeds 50 %. For marshes and

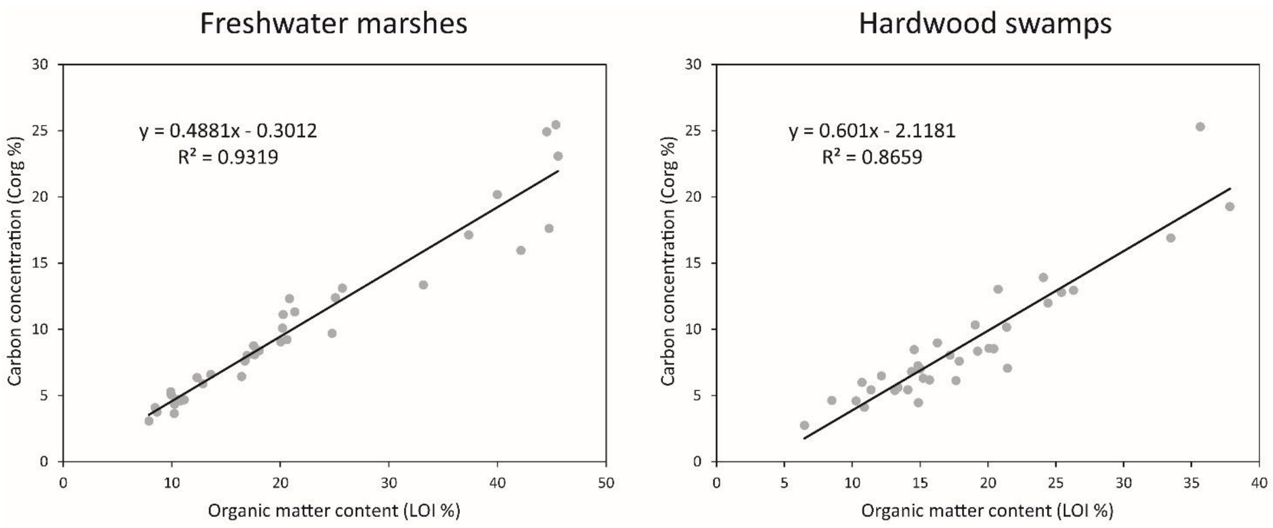

Figure 2. Relationship between organic matter content (LOI %) and organic carbon concentration (Corg %) for freshwater marshes (n=36) and hardwood swamps (n=35).

swamps, the carbon densities of the entire organic and/or organo-mineral profile were included in the calculations.

RESULTS

Synthesis of SOC densities

A substantial difference in mean SOC densities is observed between the different classes of wetlands (Figure 3). Values are highest in forested peatlands (0.064 g cm^{-3}) and coniferous swamps (0.055 g cm^{-3}). SOC densities are higher in open fens (0.053 g cm^{-3}) than in open bogs (0.048 g cm^{-3}) and hardwood swamps (0.044 g cm^{-3}). The lowest values are found in freshwater marshes (0.027 g cm^{-3}) and saltwater marshes (0.029 g cm^{-3}).

Estimating SOC mass from the thickness of the organic-rich soil

There is a strong relationship between peat thickness and SOC mass values for peatlands (R^2=0.867–0.955). The linear regression equations could thus be used to estimate SOC mass for the three subclasses of peatlands (Figure 4 and Table 2).

The relationships between the organic-rich soil layer thickness and the SOC mass are weaker for marshes and swamps than for peatlands (Figures 5 and 6). However, in this dataset, the differences (%) between measured and predicted SOC mass using the linear regression equations are low for most marsh and swamp cores (Tables 2 and S4). All relationships are statistically significant ($p<0.05$), but some assumptions of linear regression models (e.g., normality and constant variance of residuals) were not met due to the small sample size for freshwater marshes, saltwater marshes, and hardwood swamps. Hence, a non-parametric Spearman rank test showed that SOC mass was significantly correlated to soil thickness ($p<0.05$). However, R^2 values should be interpreted cautiously for the mineral wetland subclasses due to the low amount of data included in the linear regression models.

We also estimated SOC mass by multiplying peat or soil thickness by the mean SOC density of each wetland subclass presented in Figure 3. The SOC mass estimates obtained using this approach were very similar to those calculated from the regression equation for all subclasses of wetlands (Tables 2 and S4).

Estimating SOC mass in peatlands using the degree of peat humification

The analyses on the subset of 22 peat cores show that sample SOC density increased with the degree of humification (Figure 7). The only exception is for open fen category, in which the highly humified (humic) peat samples have a lower mean SOC density than the less humified fibric and mesic peat samples. This is mainly because most humic peat samples from open fens in this subset are from the lower section of one peat core characterised by

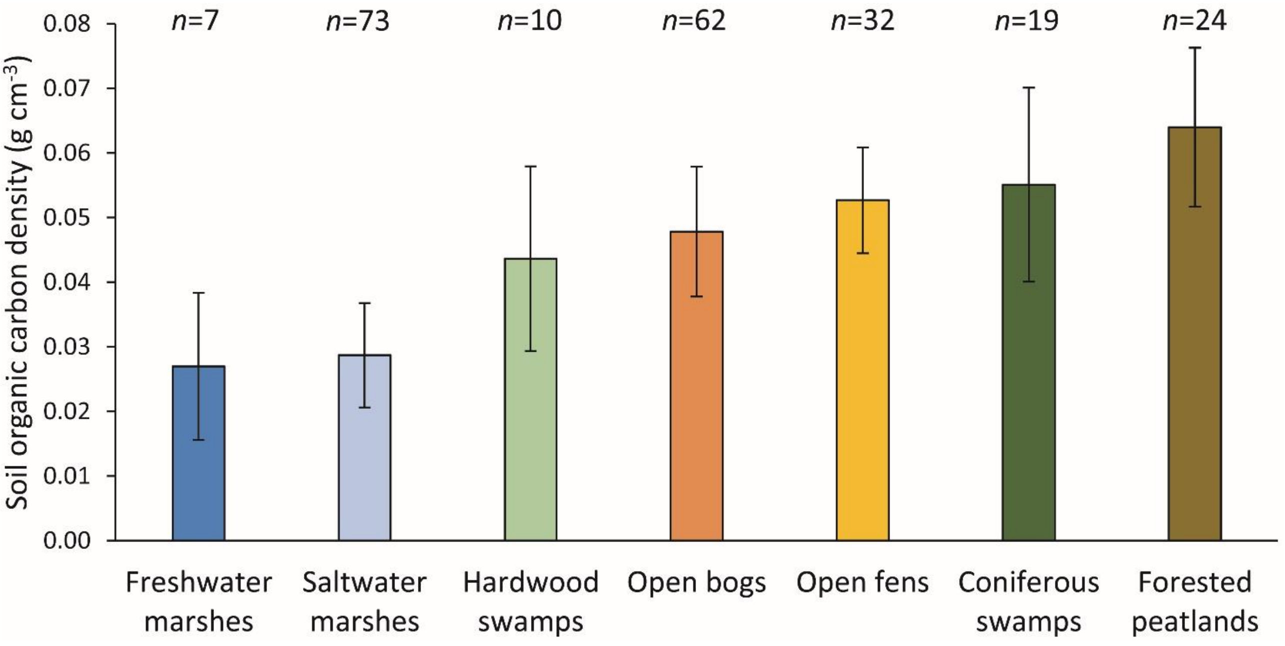

Figure 3. Mean SOC densities (± SD) for the different wetland subclasses from eastern Canada. The number of peat/soil cores included in the calculation of the mean is indicated for each wetland category.

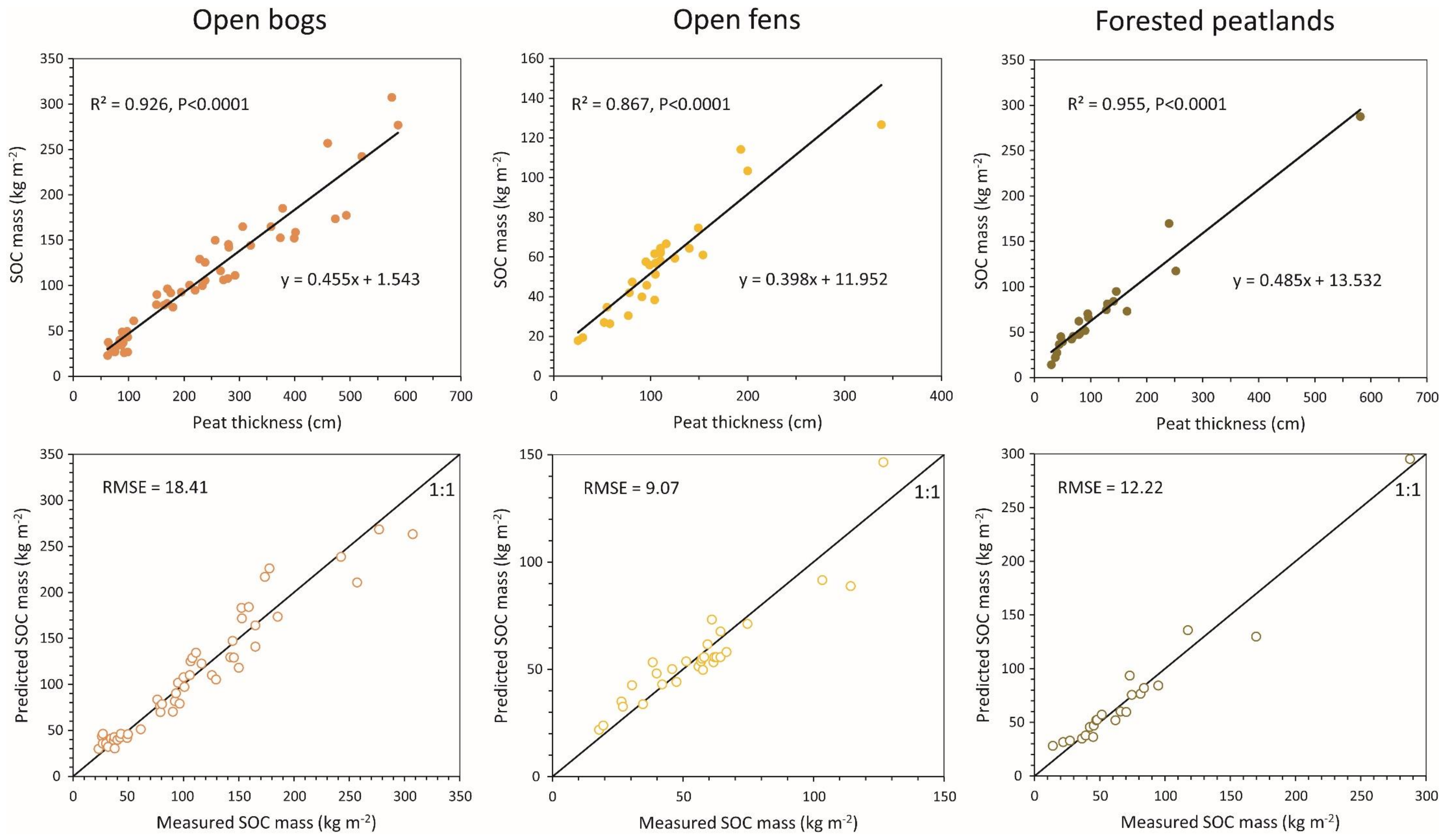

Figure 4. Relationship between peat thickness and SOC mass (upper panels) and measured against predicted SOC mass values in the three subclasses of peatlands (lower panels). RMSE : root mean square error.

Table 2. Precision of SOC mass estimates from measurements of peat/soil thickness in the different wetland subclasses using the two calculation approaches.

Wetland classes	Wetland subclasses	Number of SOC mass values[1]	Mean difference (%)[2]	
			Thickness × mean SOC density	Linear regression equation
Peatlands	Open bog	50	15.0	14.6
	Open fen	29	13.4	13.9
	Forested peatland	22	15.2	16.5
Swamps	Hardwood swamp	10	30.7	30.8
	Coniferous swamp	19	22.6	16.1
Marshes	Freshwater marsh	7	39.7	57.0
	Saltwater marsh	11	15.2	7.9

[1] Soil cores comprising both a thickness value and SOC density data at a minimum interval of 2 cm.
[2] Relative difference (% in absolute value) between predicted and measured SOC mass.

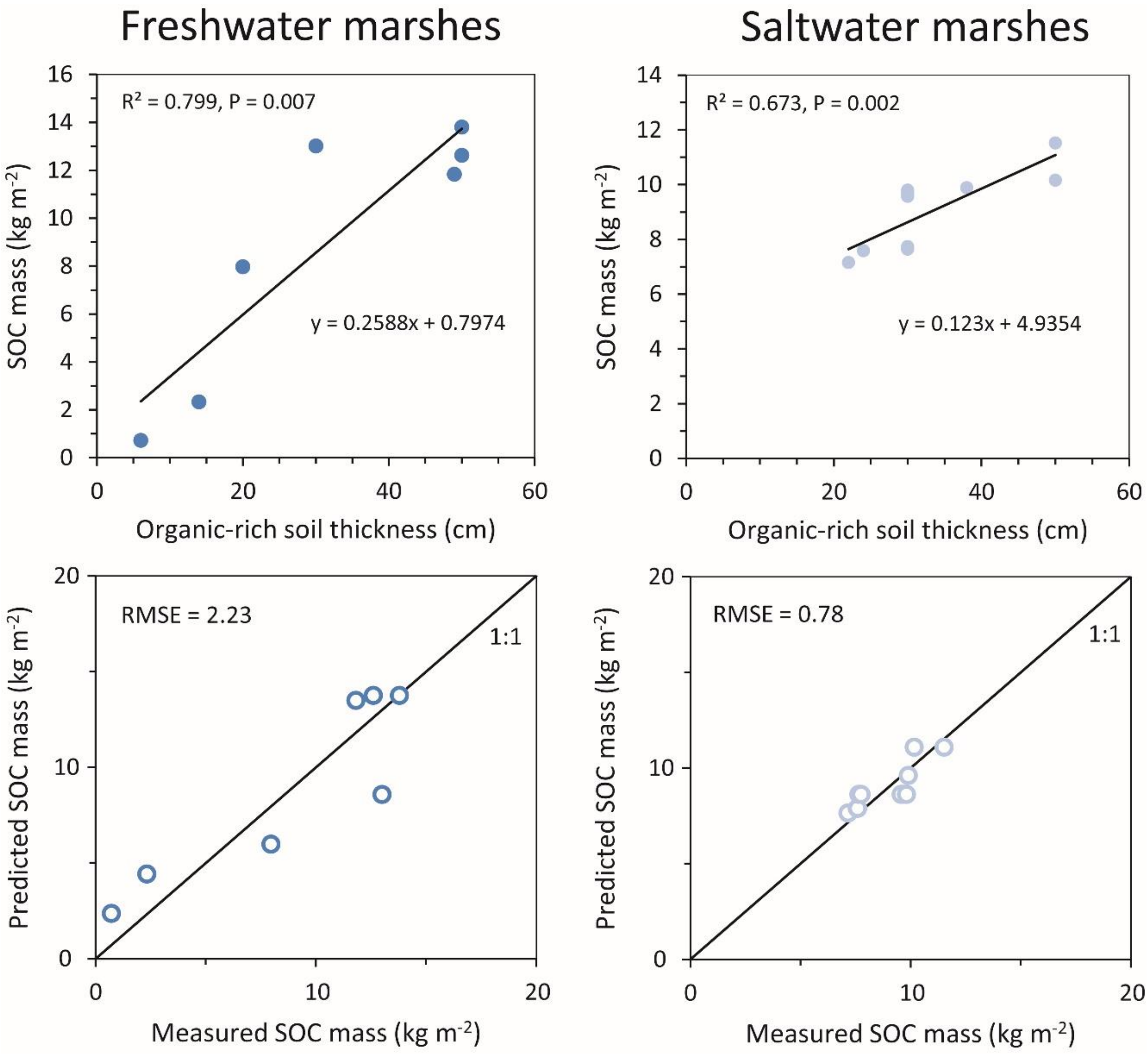

Figure 5. Relationship between the organic-rich soil layer thickness and the SOC mass (upper panel) and measured against predicted SOC mass values (lower panels) for freshwater and saltwater marshes. RMSE : root mean square error.

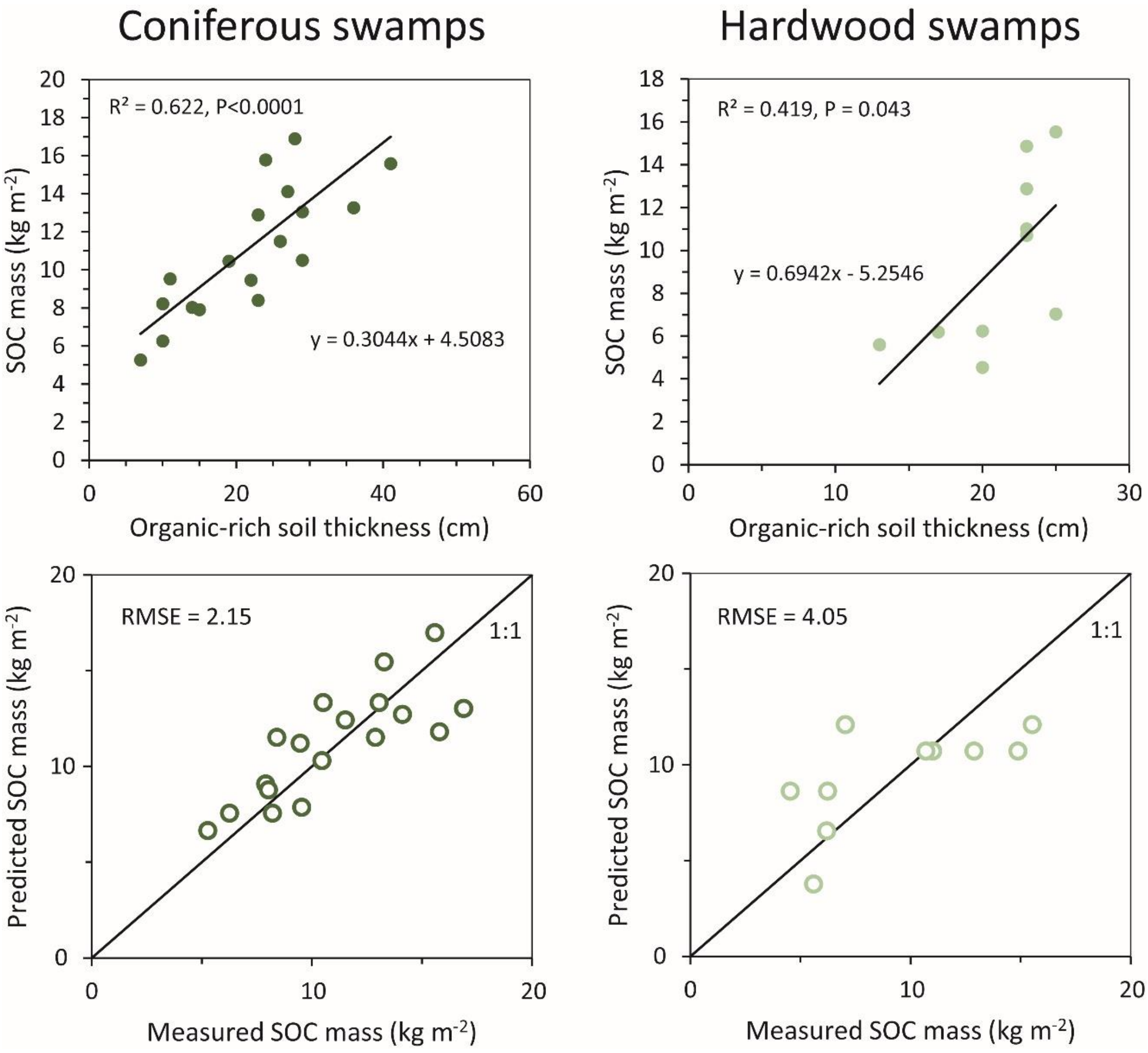

Figure 6. Relationship between the organic-rich soil layer thickness and the SOC mass (upper panel) and measured against predicted SOC mass values for coniferous swamps and hardwood swamps (lower panels).

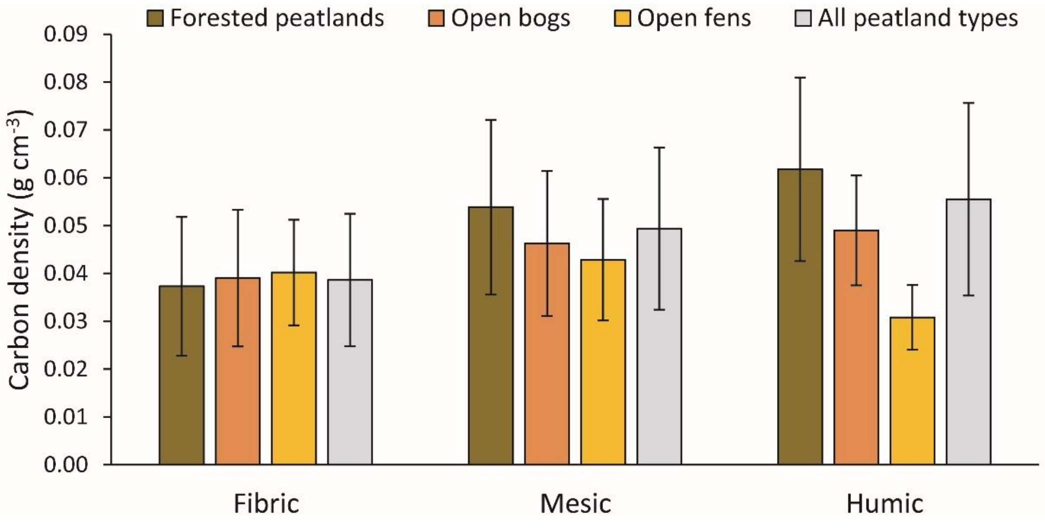

Figure 7. Mean (±SD) carbon density of peat samples (n=776) for the three main classes of humification. Fibric (von Post H1–H4) = weakly humified; Mesic (von Post H5–H6) = moderately humified; Humic (von Post H7–H10) = highly humified.

exceptionally high mineral contents (>25 %). Overall, peat profiles from forested peatlands were typically more humified than those from open fens and open bogs (Table 3), which explains the higher mean SOC density for this wetland subclass (Figure 3).

Our analyses show that the degree of humification measured within the 50–100 cm interval or for the entire peat profile (<50 cm) can be used to predict the SOC mass in peatlands (Table 3). In the subset of the analysed cores, reliable SOC mass estimates (mean difference: 16.3 %) were obtained by multiplying peat thickness by the mean SOC density calculated for each humification class of all peatland samples combined (Figure 7). More accurate SOC mass estimates were obtained by multiplying peat thickness by a mean SOC density calculated specifically for the three humification classes for each peatland subclass (mean difference: 13.9 %). However, the precision of estimates using this approach in this subset of cores is lower than the one obtained using the two calculation approaches that do not consider humification but only the peatland type (Table 2).

Table 3. SOC mass estimates using the mean carbon density calculated for each degree of humification.

Wetland type	Core name	von Post humification class	Peat thickness (cm)	Measured SOC mass (kg m^{-2})	× mean SOC density (Humification - samples per peatland type)		× mean SOC density (Humification - samples of all peatland type)	
					Predicted SOC mass (kg m^{-2})	Difference (%)	Predicted SOC mass (kg m^{-2})	Difference (%)
Forested peatlands	BEN-7	Humic	50	39.2	30.9	21.3	27.9	28.8
	BEN-6	Humic	80	48.0	49.4	3.0	44.7	6.9
	V3/V.50m	Humic	79	62.0	48.8	21.3	44.1	28.8
	CAS100	Mesic	96	66.0	51.7	21.7	47.6	27.9
	V2/V.100m	Humic	95	70.2	58.7	16.5	53.1	24.5
	Lano	Mesic	165	72.9	88.8	21.8	81.8	12.2
	TF - Lac Geai	Humic	128	74.6	79.1	6.0	71.5	4.2
	BEN-2	Humic	130	81.2	80.3	1.1	72.6	10.6
	V1/V.150m	Humic	141	83.9	87.1	3.8	78.8	6.1
	L3/L.150m	Mesic	146	94.9	78.6	17.2	72.4	23.7
	TF - Croche	Mesic	252	117.4	135.7	15.5	124.9	6.4
Open bogs	PTE2	Fibric	271	106.4	105.7	0.6	104.3	2.0
	PLU2	Fibric	238	125.5	92.9	26.0	91.6	27.1
	L1/L.250m	Mesic	399	152.4	184.6	21.1	197.8	29.8
	L3T1C2	Mesic	374	152.7	173.0	13.3	185.4	21.4
	Plaine	Fibric	357	165.0	139.3	15.6	137.3	16.8
	TOR-CT1	Fibric	473	173.5	184.6	6.4	182.0	4.9
	Lebel	Fibric	575	307.5	224.4	27.0	221.2	28.0
Open fens	TOR-LT4	Mesic	96	45.8	41.1	10.2	47.6	3.9
	Auassat	Mesic	105	57.0	45.0	21.0	52.1	8.6
	L1T1C2	Fibric	154	61.1	61.9	1.3	59.2	3.0
	Fen Cerise	Mesic	338	126.8	144.9	14.3	167.6	32.2
				Mean		**13.9**		**16.3**

DISCUSSION

In this study, we compiled a large dataset of SOC densities from peat and soil cores to develop a simple method for estimating the mass of carbon stored in wetland soils based on field measurements. The mean SOC density values calculated for temperate and boreal wetlands of eastern Canada (Figure 3) are comparable to previous regional- or continental-scale estimates. The value for saltwater marshes (0.029 g cm^{-3}) is similar to that calculated for coastal saltwater marshes throughout the United States (0.027 g cm^{-3}; Holmquist *et al*. 2018). The value for open bogs (0.048 g cm^{-3}), open fens (0.053 g cm^{-3}), and coniferous swamps (0.055 g cm^{-3}) are comparable to the estimate for northern peatlands (0.052 g cm^{-3}; Loisel *et al*. 2014).

Our synthesis highlights the lack of SOC data from mineral wetlands. Overall, the carbon dynamics of mineral wetlands remains largely understudied in temperate regions of North America and soil carbon data are lacking, especially for swamps (Davidson *et al*. 2022), and freshwater marshes (Loder & Finkelstein, 2020). Moreover, there was relatively little data available for some peatland types in temperate regions of eastern Canada, especially from forested peatlands and open fens.

Our analyses show that the SOC mass can be estimated reliably for different wetland types by measuring the thickness of the organic-rich soil layer. This can be done manually in the field by inserting a probe in the peat or soil profile until the underlying mineral deposit or bedrock is reached (see Howard *et al*. 2014). For each wetland type, SOC mass can be estimated based on a large regional dataset either by using the linear regression equation between peat or soil thickness and SOC mass or by multiplying peat or soil thickness by the mean SOC density of the corresponding wetland type. These two approaches for calculating SOC mass in our dataset provided similar estimates (Table 2). In order to improve the precision of the SOC mass estimates, more specific studies could be conducted on smaller regional datasets using the same approach and by refining the classification of wetlands. One source of uncertainty in the estimation of the SOC mass using this simple field method is that it does not take into account the full developmental history of the wetland. For instance, a peatland classified as a bog may have previously been a fen during its early developmental stage and a forested peatland may not have always been covered by trees over the past millennia.

In peatlands, our analyses show that carbon density increases with the degree of peat humification. Then, we show that accurate estimates of SOC mass can be obtained by multiplying peat thickness by the mean SOC density calculated for each humification class (i.e., fibric, mesic, humic) within a subset of peat samples. Using the degree of humification of peat profiles (e.g., 50–100 cm interval) for estimating SOC mass is a promising approach, especially considering that this method is easy to perform in the field. Our analyses show that this approach could provide reliable estimates even when the peatland type is ignored. In further studies, the relationships between carbon density and humification should be tested on larger datasets of peat cores from various peatland types.

Overall, in this dataset, SOC mass estimates are more precise in organic wetlands (peatlands) than in mineral wetlands (marshes and swamps). For mineral wetlands, the lower precision of SOC estimates (Table 2) is primarily due to the lack of empirical soil core data. Here, we provide original SOC data from hardwood swamps and freshwater marshes, which allows us to show the existing relationships between soil core thickness and SOC mass in these wetland types (Figures 5 and 6). However, further analyses of carbon density on soil cores combined with field measurement of the organic-rich layer thickness will be necessary in mineral wetlands to develop more robust regression models for estimating SOC mass in these ecosystems. Although the linear regression equations provided precise SOC mass estimates for most cores of mineral wetlands in this dataset, more statistically valid SOC mass estimates would be obtained using the other approach by multiplying the soil thickness (cm) by the mean SOC density of the corresponding wetland type.

Our observations suggest that the lower precision of SOC mass estimates for marshes and swamps compared to peatlands is also partly explained by a higher variability of SOC densities between cores and within each core in the dataset (Table S2). While peat cores are usually highly dominated by organic matter, marsh and swamp cores typically show a more variable concentration of mineral and organic matter. For instance, in coastal marshes, SOC density in cores may vary significantly along the toposequence depending on sedimentary inputs and degree of submersion (Connor *et al*. 2001). Moreover, it is more difficult in the field to differentiate the organic-rich layer from the underlying mineral soil in marshes and swamps than in peatlands, which may increase uncertainties when predicting SOC mass based on core thickness alone.

The method proposed here allows to rapidly estimate belowground soil carbon storage, which could be very useful for large-scale carbon accounting purposes. In most wetlands, especially in open peatlands, soils are by far the largest carbon pool. However, in some coniferous swamps and forested peatlands, a significant fraction of the total ecosystem carbon pool can be locked up in the aboveground woody vegetation (Magnan *et al*. 2020, Beaulne *et al*. 2021). Thus, to fully account for the carbon storage function of wetlands at the regional scale, the amount of carbon stored in aboveground woody biomass also needs to be assessed. This can be estimated in the field by measuring the diameter of shrubs and trees identified at the species level. Then, allometric equations can be used to calculate a woody biomass (e.g., Lambert *et al*. 2005) which can be converted to a carbon mass using a factor of 0.5 (Jenkins *et al*. 2006).

In this study, we presented a simple approach for estimating the mass of soil carbon stored at any study location on a wetland. If the objective of a study is to estimate the amount of carbon stored at the scale of an entire wetland ecosystem, multiple SOC mass estimates could be performed within a wetland with a sampling effort that takes into account the intra-site variability of the organic layer thickness. In peatlands, geophysical methods such as ground-penetrating radar (GPR) could be used for estimating peat thickness at high spatial resolution (e.g. Sass *et al.* 2010, Parry *et al.* 2014). The carbon stock at the scale of a wetland can thus be estimated by multiplying the mean SOC mass (kg m^{-2}) of multiple stations by the wetland area (m^{-2}).

The rapid field method proposed here could be applied in different wetland regions of the world where carbon density data from soil cores are available. For instance, it would be interesting to test this approach for estimating the SOC mass in tropical peatlands in which peat deposits are often very thick and where it is logistically difficult to collect and carry peat cores. The widespread use of such a method, that does not require to collect cores and perform laboratory analyses, could allow to improve knowledge of the carbon storage function of different wetland types and better mapping the spatial distribution of their carbon stocks. These data are essential for improving wetland conservation strategies and quantify the carbon losses associated with the alteration or destruction of these ecosystems under anthropogenic pressures.

ACKNOWLEDGEMENTS

This study was funded by the Ministère de l’Environnement et de la Lutte contre les Changements Climatiques (MELCC) through the Plan pour une économie verte (PEV) fund to Michelle Garneau. We would like to thank Daniel Lachance and Laurence Paradis for fruitful discussions and advice. We also thank two laboratory assistants (Alexandre Gauthier, Reno Bouchard) for their precious help in the analyses of new soil cores.

AUTHOR CONTRIBUTIONS

GM and MG conceived the study and wrote the first draft of the manuscript with input from all authors. JB, NS, LP, participated in field work, analysed and synthesised data. PJHR, SP and ML provided carbon density data from peat cores. All the authors provided critical feedback and contributed to the final version of the manuscript.

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Submitted 31 Jul 2022, revision 23 Oct 2022
Editor: Stephan Glatzel

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Supplement (available for separate download) :
Excel file containing metadata for peat and soil cores used in the study (Tables S1–S4).