FORESTED WETLANDS

Long-Term Carbon Accumulation in Temperate Swamp Soils: a Case Study from Greenock Swamp, Ontario, Canada

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Abstract
Wetlands that develop peat are a globally significant pool of soil carbon. While some wetland types such as bogs and fens are well characterized by the consistent development of carbon-rich peat, swamps soils are more variable both in terms of their carbon densities and accretion rates. Subcategorizing swamps by forest type may be a useful way of understanding this variability. Here we provide a case study of carbon accumulation in two distinct forest stands of Greenock Swamp located in the Great Lakes – St Lawrence mixed forest region in Bruce County, Ontario, Canada: Acer-Fraxinus (maple-ash) swamp (i.e., broad-leaf swamp) prevalent across the site, and a Thuja occidentalis (cedar) swamp stand (i.e., needle-leaf swamp). Organic matter and organic carbon contents were analyzed among seven broad-leaf swamp soil cores and one needle-leaf swamp core collected from Greenock Swamp. The broad-leaf swamp cores had peat depths ranging from 18–60 cm with a mean organic matter content of 54% and an organic carbon content of 34% of dry mass. The needle-leaf swamp core had at least 4 m of almost homogeneous peat with a mean organic matter content of 89%. Radiocarbon dating indicates that the broad-leaf swamp accumulates peat episodically, but can contain organic matter thousands of years old; the needle-leaf swamp shows continuous peat accumulation since the Middle Holocene. While broad-leaf swamp soils contain lower carbon stocks than needle-leaf swamp soils, they extend over large areal extents at Greenock Swamp and elsewhere in the temperate zone and contain important pools of recalcitrant organic matter, in some cases thousands of years old. Thus, both swamp types need to be considered to fully represent the carbon pools and potential sink of temperate wetlands.

Keywords Swamp · Forested Wetland · Peat · Long-term carbon accumulation · Great Lakes

Introduction
Research on soil carbon storage in peatlands has historically focused on boreal and sub-arctic bogs and fens (Loisel et al. 2014) and tropical peat swamp forests (Page et al. 2011). These wetland types are known to develop deep peat profiles that store large stocks of soil carbon (Yu et al. 2010). They are also sensitive to changes in temperature and hydrology, thus have been a priority under the context of climate change. While it has long been well known that mid-latitude swamps including needle-leaf, broad-leaf or mixed swamps also contain important soil carbon stocks (Warner et al. 1984; Chimner et al. 2014; Middleton 2020; Newby et al. 2000; Ott and Chimner 2016; Sleeter et al. 2017; Davidson et al. 2022), many available regional and global scale peatland-carbon studies have omitted these wetland types altogether, due to difficulties mapping them and lack of ground data to parameterize models of carbon accumulation in swamp settings (Yu et al. 2010; Bona et al. 2020). Moreover, the Second State of the Carbon Cycle Report (Kolka et al. 2018) emphasizes the importance of swamps, estimating that temperate swamps store up to 50% of all wetland carbon in North America, despite only covering 33% of wetland area. Locally in Southern Ontario, Canada, swamps are estimated to store 71% of wetland carbon over 75% of wetland area with large variations in soil carbon stocks across forest types and locations (Byun et al. 2018). Despite their large areal extent and the growing appreciation for swamp soil carbon stocks in middle latitude regions, more ground data...
are needed to better understand and quantify the variability in soil carbon stocks in the various types of temperate zone swamps (Kendall et al. 2021; Davidson et al. 2022).

Our understanding of peat accumulation in middle latitude swamps is complicated by the fact that many have experienced significant human alteration. Common types of alteration in swamps include logging and drainage, which lowers the water table and promotes carbon loss through decomposition of organic matter (Li et al. 2021). Alteration may leave a swamp functionally or ecologically dissimilar from pre-disturbance conditions or even converted to an entirely different land cover type. In Southern Ontario, ~18% of treed swamps and ~47% of shrub swamps have been converted to new land cover types since colonial settlement (Byun et al. 2018). Given ongoing anthropogenic impacts on wetlands in populated middle latitude regions, there is a need for an improved understanding of swamp soil carbon storage to facilitate land use planning and management decisions that protect soil carbon stocks and promote nature-based climate solutions.

Swamps are described in the Canadian Wetland Classification System (National Wetlands Working Group 1987) as mineral or organic soil wetlands with >30% cover of tall, woody vegetation. Mineral swamp soils in the Gleysol order are typified by features caused by anoxic, reducing conditions; Humic or Peaty Phase Gleysols show an organic surface horizon (Soil Classification Working Group 1998). Organic swamp soils are subcategorized into Humisols or Mesisols depending on the degree of organic decomposition (Soil Classification Working Group 1998). Paleoecological studies have documented temperate swamp soils with both entirely mineral soils, organic soils, or a combination. Some organic swamp soils contain peat sections, either at the surface, or at depths >40 cm, and exceeding several meters in the case of needle-leaf swamps (McLachlan and Brubaker 1995; Bunting and Warner 1999; Newby et al. 2000; Craft et al. 2008; Ott and Chimner 2016). In addition to diverse soil types, North American swamps are associated with a range of hydrological regimes including riparian, floodplain, lakeside or coastal settings, or zones of groundwater discharge (Dahl and Zoltai 1997). Vegetation assemblages are also highly diverse across temperate zone swamps, including broad-leaf, needle-leaf, thicket, or mixed assemblages (Riley 1994). Greater peat thicknesses and larger soil carbon stocks in needle-leaf swamps of temperate North America are relatively well documented, for example in both minerotrophic and acid swamps dominated by Thuja occidentalis (Riley 1994; Zoltai and Vitt 1995; Ott and Chimner 2016). In contrast, there is less information available on soil organic matter content, presence of peat, peat thickness or age in broad-leaf swamps. These are often classified as mineral-soil swamps and assumed to be less important from a soil carbon perspective, although organic soils ~60 cm in thickness and continuous peat accumulation have been documented in Fraxinus nigra (Black ash) swamps (Chimner et al. 2014).

The aim of this study is to compare peat depths, ages, carbon densities and long-term rates of apparent carbon accumulation across a series of cores in a regionally significant swamp site in Southern Ontario, Canada. We contribute new measurements of peat depths, ages and carbon stocks in broad- and needle-leaf swamp soils, addressing key data gaps identified in larger-scale syntheses (Bona et al. 2020; Davidson et al. 2022). Given the increased lability of broad-leaf tree tissues, and the numerous examples of needle-leaf swamps with deep peat profiles, we hypothesize that the broad-leaf swamp soils will have less overall peat accumulation, but despite lower accumulations, they must be considered as key components of regional carbon budgets.

**Methods**

**Study Area**

Greenock Swamp is an 8,000-hectare wetland located in the Teeswater River watershed of Bruce County, Ontario, Canada (Fig. 1). It is one of the largest continuous-area wetlands in Southern Ontario (Riley 2013). It is mainly occupied by deciduous, broad-leaf swamp, with small, localized stands of needle-leaf swamp dominated by Thuja occidentalis (White cedar), marsh and bog covering approximately <10% of the wetland extent (Saugeen Valley Conservation Authority 1979). Anthropogenic impacts include a nineteenth century drainage ditch and canals that were dredged to transport timber during early twentieth century (Saugeen Valley Conservation Authority 1979). The bedrock beneath the swamp is Silurian sandstone, dolomite and shale, and is overlain by the glacial Norfolk formation (Chapman and Putnam 1984) with lake effect snow and groundwater discharge supporting swamp hydrology (Byun et al. 2021). Most of the site is either seasonally or permanently flooded. The mean annual temperature is 6.5°C and the mean total annual precipitation is 1100–1200 mm (Environment and Climate Change Canada 2021).

Three sites in Greenock swamp were investigated: GS02, GS04 and GS05 (Fig. 1). GS02 is in the small needle-leaf swamp zone of Greenock Swamp. Located northeast of Schmidt Lake, this site is characterized by a closed canopy forest of Thuja occidentalis (White cedar) and hummock and hollow terrain. Diameters at breast height (DBH) for the mature cedar trees ranged from 10–20 cm. A small number of Abies balsamea (Balsam fir) (1–2 m tall) were
also present. A limited number of broad-leaf trees exist in this zone including birch (*Betula alleghaniensis*, DBH 15–25 cm), ash (*Fraxinus* spp.), and maple (*Acer rubrum*). *Sphagnum* moss, grass and ferns make up the understory. There was no standing water at the time of sampling.

Sites GS04 and GS05 are located within the broad-leaf swamp zone of Greenock Swamp adjacent to Cunningham Lake (Fig. 2). This vegetation class dominates the swamp landscape, extending over about 90% of the 8000-ha wetland extent. Tree cover at both sampling sites mainly consists of silver maple (*Acer saccharinum*), with *Ulmus americana*, *Betula alleghaniensis*, *Acer rubrum* and *Fraxinus* spp. also present. GS04 had a moderately closed canopy with trees with DBHs ranging from 15–30 cm. GS05 had a more open canopy and trees with lower DBH (10–15 cm). Both sites had standing water depths ranging from 5–50 cm, however GS04 showed more visual evidence of seasonal low water levels as well as a possibly anthropogenic, completely linear flow channel. GS04 also showed more beaver activity than GS05 with the presence of several lodges and felled trees showing cut marks.

**Swamp Soil Coring**

Field work at Greenock Swamp was carried out September 2019. A total of eight cores were collected from GS02, GS04 and GS05 (Fig. 1; Table 1). Locations for coring were chosen to capture localized microtopographic variability including wet hollows with limited standing water, and pools with standing water 30–50 cm in depth at the time of sampling. All cores were collected in 50-cm drives using a Russian peat corer except for core GS02-19–02 which was collected in 1-m drives (also with a Russian peat corer). At GS02, the top 10 cm was also sampled by cutting a surface monolith using a serrated knife. All cores were sampled to refusal, then tightly...
swapped plastic wrap then foil, and stored in split PVC pipe. Cores were placed in cold storage at 6 \degree C prior to analysis.

**Swamp Soil Characterization and Radiocarbon Dating**

The GS04 and GS05 cores were cut into contiguous 2-cm intervals. A 6.28-cm\(^3\) subsample was cut from the centre of the sample using a cylindrical sampling plug. The GS02 (needle-leaf swamp) core was cut in half lengthwise. One half was cut into contiguous 4-cm intervals for bulk density and loss-on-ignition. A 4\times2\times1.5 \text{ cm} right-angled tool was used to extract contiguous 12-cm\(^3\) sub-samples. All sub-samples were then weighed and dried to constant mass at 95 \degree C. Bulk density was calculated by Dry Bulk Density (g/cm\(^3\)) = (Dry weight)/(fresh volume) (Chambers et al. 2010).

For loss-on-ignition, 0.5–1.0 g of the dried sample from every sub-sampled interval of each core was placed in a clean crucible of known mass. Samples were covered then combusted in a muffle furnace at 550 \degree C for 4 h, the re-weighed for organic matter estimates (Chambers et al. 2010; Heiri et al. 2001). The samples were then placed back in the furnace at 950 \degree C for 2 h to estimate carbonate content. The remaining mass fraction is classified as residual. Loss-on-ignition was performed on all cores. Cores were also classified by soil type using the Canadian System of Soil Classification (Soil Classification Working Group 1998).

Total carbon (TC) and total inorganic carbon (TIC) content were directly measured by elemental analysis only on a sub-set of the samples from cores GS04-01 and GS05-04 to verify the organic matter by loss-on-ignition to organic carbon conversion. A total of 33 dried samples (every 2 cm
for GS04-01; every 4 cm for GS05-04) were ground to a fine powder using a Retsch MM200 Oscillating Mill, and analyzed using the SSM-5000a TOC Solid Sample Combustion unit of the Shimadzu TOC-L TOC/TN analyzer at the ANALEST facility (Department of Chemistry, University of Toronto). The instrument was calibrated with glucose and sodium carbonate standards. To measure TIC, samples were first acidified with 0.5 ml of phosphoric acid and then heated to 200°C. Total organic carbon (TOC) was calculated as the difference between TC and TIC, and was compared to organic matter content as determined by loss-on-ignition.

The relationship between organic matter and organic carbon contents depends on the type of organic matter and the degree of decomposition. For this reason, it has been recommended to develop wetland type specific conversion factors (Klingenfuß et al. 2014). We used the samples from GS04-01 and GS05-04 for which both LOI and direct TOC measurements were available to show that in these samples, the ratio of total carbon to organic matter is 51% (Supplementary Fig. 1), similar to the 0.5 conversion factor commonly used in the literature. For core GS02, TOC and LOI data from a previously collected core from the same site at Greenock Swamp (Byun et al. 2021) were used to convert organic matter determinations from loss-on-ignition to TOC. Carbon density (g C m$^{-3}$) was calculated as the product of bulk density (g cm$^{-3}$) and carbon content (g g$^{-1}$); carbon stocks (g cm$^{-2}$; kg m$^{-2}$) by depth section (ie., 0–30 cm, after Nahlik and Fennessy 2016) were calculated as the product of carbon densities (g cm$^{-3}$) and section thickness (cm).

Wood pieces of dry mass > 20 mg were selected from core samples for radiocarbon dating. Where no wood pieces of sufficient mass in highly humified core sections could be found, composite radiocarbon dating of combinations of smaller wood and plant fragments was done. In those cases, 1–3 cm$^3$ of sediment was removed from the core using a ceramic spoon and mixed with 5% warm KOH. The mixture was then sieved at 90 μm and rinsed with deionized water until the filtrate was clear. The residual filtrate was picked though on a stereo-microscope to extract wood or leaf fragments. Radiocarbon dating was performed at the the André E. Lalonde Accelerator Mass Spectrometry Laboratory at the University of Ottawa (Canada), and ages were calibrated using IntCal20 (Reimer et al. 2020). Median calibrated ages were used to estimate peat accretion and long-term apparent rate of carbon accumulation in the GS05-4 and GS02 cores (Korhola et al. 1995; Packalen and Finkelstein 2014). To estimate the mean rate of peat vertical accretion, the depth of organic section was divided by basal age. For cores with multiple radiocarbon dates, peat accretion was calculated using weighted averages by depth interval. Apparent rates of carbon accumulation (aCAR, g C m$^{-2}$ yr$^{-1}$) were calculated by multiplying carbon density (g C cm$^{-3}$) by accretion rate (cm yr$^{-1}$) for the specified depth range.

**Results**

**Greenock Swamp Core Characterization**

The broad-leaf swamp cores are characterized by organic accumulation confined to the upper 60 cm of the core (Table 1). The three cores from GS04 have similar depths in the surficial organic layers, ranging from 18–22 cm. At site GS05 where smaller-diameter trees suggested more persistently high water levels, the organic sections are deeper but also more variable in length, ranging from 21–60 cm. The organic sections in all GS04 and GS05 cores have a crumbly to pasty texture, dark brown to black colour and are generally well humified but with some visible rootlets and wood pieces. The transition from peat to inorganic soil varies from abrupt to gradual. The inorganic sections are dark grey in colour and vary from sandy to silty in texture. No visible plant fragments were observed in the inorganic section of these cores. Cores taken from hollows had deeper organic sections than cores taken from pools across both sites. Cores GS05-02 and GS05-04 were classified as Organic Humisols with > 40 cm of humified organic material (Kroetsch et al. 2011). The rest of the broad-leaf cores were classified as Humic Gleysols, with < 40 cm of highly humified material, underlain by gleyic sediments (Soil Classification Working Group 1998).

The mean bulk density of the organic section in the broad-leaf swamp cores is 0.19 g/cm$^3$ and the mean organic matter content is 54.27%. Below the surface organic-rich layer, bulk density increases, and organic matter decreases markedly (Figs. 3 and 4). Mass percentages of inorganic carbon (carbonate) were below detection until the lowest sections of all broad-leaf swamp cores, and did not exceed 10% in any of the lowermost samples (Supplementary Fig. 2). The carbon in these cores was overwhelmingly organic thus we do not consider the inorganic fraction further. Areal carbon stocks calculated in cores with direct measurements of carbon by elemental analysis were for GS04-01, 13.5 kg C m$^{-2}$ for a depth range of 0–20 cm, and for GS05-04, 36.0 kg C m$^{-2}$ for a depth range of 0–48 cm. These values are similar to those reported for comparable depths in estuarine woody or other forested wetland types in the United States (Nahlik and Fennessy 2016).

The needle-leaf swamp core (GS02) consists of uniform dark brown, moderately humified peat, with two sections consisting of solid undecomposed woody material (150–170 cm and 230–366 cm). Although this core was sampled to refusal, no inorganic sediment was observed at the bottom of the core; thus, refusal was most likely a larger log and organic accumulation likely continues below what was captured in the peat corer. This soil is classified as an Organic Mesisol / Humisol due to thick
accumulation of moderately decomposed organic material. There is little variability in organic matter content or bulk density through the core. Mean bulk density was 0.093 g cm\(^{-3}\) and mean organic matter content 89.5%. The slight increases in organic matter around 160 cm and 260 cm correspond to sections of the core that were entirely filled with undecomposed wood (Fig. 4). Areal carbon stocks (calculated following Byun et al. 2021) were \(~ 60 \text{ kg C m}^{-2}\) for depths 0–120 cm in the needle-leaf swamp core (GS02), which exceeds mean values for forested wetland types included in the synthesis of Nahlik and Fennessy (2016).

**Radiocarbon Dating and Carbon Accumulation Rates**

The dated materials from the broad-leaf swamp cores GS05 and GS04 had a large discrepancy in ages, varying between century-old to millennia-old. The century old material was from the two shallowest depths, GS04-02 12–14 cm and GS05-04 22–24 cm. However, GS05-01 24–26 cm returned a Middle Holocene age of 7244 yrs BP. Core GS05-04 was sampled at two depths and returned both a century-old age and a deeper millennia-old age. GS02 returned two Middle / Late Holocene ages (Table 2).

Radiocarbon dates were used to estimate average long-term apparent rates of peat vertical accretion and carbon accumulation, but these values for the broad-leaf swamp cores must be interpreted with caution as these sites are not characterized by continuous accumulation of organic matter. For GS02-19–02, accretion rates were estimated by assuming linear rates between radiocarbon dates. Apparent rates of organic carbon accumulation (aCAR) (Clymo 1984; Young et al. 2021) were calculated for cores with direct carbon measurements only (Table 3). In GS05-04, peat accretion and aCAR values differ by an order of magnitude from depths 23 cm to 39 cm, suggesting strongly non-continuous regime of peat accumulation. These aCAR values cannot be directly compared to the needle-leaf swamp core (GS02-19–02) showing accumulation rates consistent with those documented in peat cores from other needle-leaf swamp sites dominated by *Thuja occidentalis* (Ott and Chimner 2016) and boreal bogs and fens (Bysouth and Finkelstein 2021).
Discussion

The results from Greenock swamp show considerable heterogeneity in swamp soil properties. Both GS05-02 and GS05-04 (broad-leaf swamp sites) have >40% organic matter content for >40 cm depth (Fig. 4), which makes them Organic soil wetlands under the Canadian wetland classification system (National Wetlands Working Group 1987). Although GS05-01 is directly adjacent to GS05-02, it has less organic material only up to ~30 cm depth and is classified as a mineral soil wetland. Still, apart from the surface 2 cm, GS05-01 has organic matter content consistently above 40%. This pattern of organic soil adjacent to mineral soil is repeated with GS05-03 and GS05-04. Despite being separated by only a few meters distance and sharing a similar vegetation assemblage, GS05-04 meets the definition of organic soil, whereas GS05-03 does not.

Table 2 Radiocarbon age estimates for Greenock Swamp samples, calibrated with OxCal v4.4 (Bronk Ramsey 2009) and the IntCal20 calibration curve (Reimer et al. 2020)

| Lab ID     | Core     | Sample Depth (cm) | Dated Material          | Conventional $^{14}$C age (14C yrs BP) | 2-$\sigma$ Calibrated age (yrs BP) | Median calibrated age (yrs BP) |
|------------|----------|-------------------|-------------------------|----------------------------------------|-------------------------------------|---------------------------------|
| UOC-13851  | GS04-02  | 12–14*            | Wood                    | 141 ± 25                               | 120–52                              | 120                             |
| UOC-13432  | GS05-01  | 24–26*            | Wood                    | 5410 ± 27                              | 6288–6186                           | 6240                            |
| UOC-13852  | GS05-02  | 55–57*            | Wood and plant material | 6326 ± 31                              | 7316–7235                           | 7240                            |
| UOC-13431  | GS05-04  | 22–24             | Wood                    | 127 ± 25                               | 151–9                               | 110                             |
| UOC-13853  | GS05-04  | 38–40*            | Wood and plant material | 3961 ± 26                              | 4450–4381                           | 4430                            |
| UOC-13433  | GS02-19–02 | 165–166           | Wood                    | 3071 ± 30                              | 3366–3209                           | 3290                            |
| UOC-13434  | GS02-19–02 | 262–266           | Wood                    | 4005 ± 25                              | 4522–4418                           | 4480                            |

* indicates a basal depth (<10 cm above base of the organic section)
Given that swamp soil organic carbon is consistent with other needle-leaf swamps including other cedar swamps common in eastern North America (Davidson et al. 2022; Newby et al. 2000; Ott and Chimner 2016; Wesley et al. 2017), transitioning to typical highly inorganic, gleyed sediments. The broad-leaf swamp cores, despite the fact that most or all of the year, whereas the soils from the hollows are seasonally exposed. Water-saturated, anaerobic conditions are preferable for minimizing organic matter decomposition in a system with no water flow. However, a system with streamflow will behave differently. Streamflow hinders the accumulation of particulate organic matter due to its erosive powers (Bernal and Mitsch 2012). In forested wetlands, streamflow can remain relatively stable throughout the year if the wetland is connected to a large aquifer (Verry 1997). The pools in the broad-leaf swamp zone at Greenock Swamp likely result from natural channelization and experience streamflow throughout the year supported by groundwater discharge (Byun et al. 2021), explaining the lower organic matter accumulation relative to hollows.

In Greenock Swamp, in addition to hydrology, vegetation contributes to the delineation between organic and mineral soils. The broad-leaf swamp cores, despite the fact that some were classified as mineral soils and others organic, in general all had less than 1 m organic material before transitioning to typical highly inorganic, gleyed sediments. This contrasts with the needle-leaf site, with >4 m of peat, consistent with other needle-leaf swamps including other cedar swamps common in eastern North America (Davidson et al. 2022; Newby et al. 2000; Ott and Chimner 2016; Warner et al. 1984). Given that swamp soil organic carbon is mainly derived from the plants growing in situ, the biochemical properties of overlying swamp vegetation will impact organic matter quality and size of resulting carbon stocks (Uhelski et al. 2022). Temperate broad-leaved trees produce more litter than needle-leaved trees owing to annual leaf loss; however, despite having more litter, topsoil in broad-leaved forests frequently contains less organic carbon due to high lability (Cornwell et al. 2008; Peng et al. 2020).

While labile leaves and stems decompose rapidly and a small fraction becomes incorporated into soil organic matter as humic materials through mineral stabilization (Cotrufo et al. 2015), more recalcitrant material such as lignin-rich wood, is incorporated into soil as structural compounds by physical transfer. For this reason, leaf and stem material is commonly not preserved at depth in swamp soils, whereas woody material may remain relatively undecomposed for much longer periods of time and consequently may be found at great depths, as shown in the Greenock Swamp cores (Table 2) and widely elsewhere (Gholz et al. 2000; Middleton 2020). The presence of wood can also reduce decomposition of other organic materials present in soil through the leaching of polyphenols, which inhibit microbial metabolism and extracellular enzyme activities (Fenner and Freeman 2020).

Neither cores from the hollows nor the pools from GS05 showed evidence for stable rates of accumulation of organic matter, meaning that continuous peat age-depth models in the broad-leaf forest zone of Greenock Swamp could not be developed (Table 3). Surface flows likely prevent the stable accumulation of organic matter in the pools and channels whereas in the hollows, seasonal water table depth fluctuations promote partial oxidation of surface soil organic matter, particularly during late growing season (Trettin et al. 2020).

The radiocarbon dates from GS05-04 and GS05-01 corroborate the episodic accumulation of organic matter in broad-leaf swamp soils. The two dated cores from this zone returned a difference in age of approximately 6000 years for a depth of 24 cm. Such a large disparity suggests that the soils from these cores can contain very old material in close proximity to young material as a result of complex hydrology involving surface flows and seasonal water table drawdown, coupled with variability in stability of organic matter inputs. In the few examples of broad-leaf swamps that have been dated with radiocarbon, continuous models of peat accumulation have similarly not been recorded (Watts 1979; Turton and McAndrews 2001; Momsen 2007). Most of the work done on long-term wetland carbon accumulation has been done in the context of continuously accumulating peat (Charman et al. 2013; Garneau et al. 2014; Loisel et al. 2017). This framework does not suit broad-leaf swamp systems such as Greenock Swamp where peat accumulates episodically, because this approach can result in misleadingly

### Table 3

| Core       | Rate of organic sediment accretion (mm yr$^{-1}$) [depth range, cm] | aCAR (g C m$^{-2}$ yr$^{-1}$) [depth range, cm] |
|------------|---------------------------------------------------------------------|-----------------------------------------------|
| GS04-02    | 0.69 [0–13]                                                        | -                                             |
| GS05-01    | 0.040 [0–25]                                                       | -                                             |
| GS05-02    | 0.077 [0–56]                                                       | -                                             |
| GS05-04    | 1.3 [0–23]                                                         | 53.1 [0–23]                                   |
| GS05-04    | 0.087 [0–39]                                                       | 6.6 [0–39]                                    |
| GS02–19–02 | 0.49 [0–165.5]                                                     | 24.1 [0–165.5]                                |
| GS02–19–02 | 0.83 [165.5–264]                                                   | 42.7 [165.5–264]                             |
| GS02–19–02 | 0.62 [0–264]                                                       | 30.9 [0–264]                                 |
high (or low) aCAR values. Further research is needed to address the under-representation of broad-leaf swamps and their potential for long-term carbon storage through episodic accumulation.

**Conclusion**

This research investigated long-term carbon accumulation across two swamp types in Greenock Swamp. Seven cores were collected from the *Acer-Fraxinus* broad-leaf swamp that dominates the site, as well as an additional single core from a *Thuja occidentalis* needle-leaf swamp present in a small area of the wetland complex. The broad-leaf swamp cores had shorter peat depths, higher bulk densities, lower organic matter content and areal carbon stocks compared to the needle-leaf swamp core, but extend over a larger area (Fig. 1). Radiocarbon dating of these cores also suggests that soil in the broad-leaf zone accumulates peat episodically, whereas the needle-leaf zone accumulates peat continuously, more similar to bog or fen systems. The differences between the broad- and needle-leaf zones are likely related to hydrology, with greater streamflow and seasonal water table change leading to denser, more humified soils in the broad-leaf zone, as well as differences in the organic matter quality supplied by broad-leaf vs needle-leaf stands. While apparent rates of carbon accumulation cannot be easily calculated for broad-leaf swamps, the data presented here suggest that the existing carbon stocks in these systems developed over thousands of years. Consequently, they are an important carbon pool not easily replaced in wetland restoration, and must be considered in inventories and land-use planning to support climate change mitigation. Despite the shorter peat profiles in the broad-leaf zone, the overall higher soil bulk density and large area extent both at Greenock Swamp and elsewhere across the temperate zone, mean this swamp type also a regionally important carbon pool, as already shown for cedar and other needle-leaf swamps.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s13157-022-01641-8.

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**Authors’ contributions** ED: Data curation, Formal analysis, Investigation, Writing – Original Draft; EB: Conceptualization, Data curation, Methodology, Writing – review and editing; SAF: Conceptualization, Data curation, Funding acquisition, Supervision, Writing – review and editing.

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**Data availability** Datasets will be made available via figshare.com.

**Declarations**

**Conflicts of interest/Competing interests** The authors declare no competing interests.

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