Long-term peat accumulation in temperate forested peatlands (*Thuja occidentalis* swamps) in the Great Lakes region of North America

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SUMMARY

Peatlands are being mapped globally because they are one of the largest pools of terrestrial carbon (C). Most inventories of C have been conducted in northern *Sphagnum* dominated peatlands or tropical peatlands. Northern white-cedar (cedar, *Thuja occidentalis* L.) peatlands are amongst the most common peatland types in the Great Lakes Region of North America, yet there is no information on their C pool sizes or rates of C accumulation. Therefore, the main objectives of this study were to determine: 1) the ages of cedar peatlands; 2) the amount of C stored in the peat profile; and 3) the apparent long-term rate of C accumulation. We sampled 14 cedar peatland sites across northern Minnesota and the Upper Peninsula of Michigan, USA. Cedar peat was found to be derived mostly from wood and to have an average thickness of 1.12 m (range 0.3–3.25 m). Basal dates indicated that cedar peatlands were initiated between 1,970 and 8,590 years ago, and they appear to have been continuously occupied by cedar. Long-term apparent rates of C accumulation (LARCA) ranged from a low of 6.4 g C m^{-2} yr^{-1} to a high of 39.7 g C m^{-2} yr^{-1}, averaging 17.5 g C m^{-2} yr^{-1}. Cedar peatlands tend to be shallower than *Sphagnum* peatlands in the region but, due to their higher bulk density (average 0.16 g cm^{-3}), they contain high amounts of C with our sites averaging ~80 kg C m^{-2}. Thus, they represent a regionally important pool of C.

KEY WORDS: carbon, LARCA, northern white-cedar, woody peat

INTRODUCTION

Peatlands accumulate carbon (C) due to primary production exceeding decomposition and other losses (Clymo 1984). They are important in the global C budget, storing > 600 Gt C since the last glacial maximum (Yu *et al*. 2010). Peatlands store C at a disproportionately greater rate than upland ecosystems. They have been found to cover only ~3 % of the global land area, but store ~30 % of the worlds' soil C (Gorham 1991). Factors such as water table depth, plant community type and climate all affect the type and amount of peat C stored in each peatland (Loisel *et al*. 2014).

Peat can be formed from many types of plants; with *Sphagnum* mosses, herbaceous plants and trees all being capable of producing deep peat deposits (Rydin & Jeglum 2013). Tree-dominated peatlands form a distinctive peatland type that is commonly called peat swamp or forested peatland. Peat swamp forms woody (silvic) peat, often with low bryophyte and herbaceous cover. The large differences between peat types (e.g., treed *versus* herbaceous *versus* *Sphagnum* moss) can result in important differences in physical and chemical attributes, which can in turn strongly influence C cycling (Bridgham *et al*. 1998). For instance, *Sphagnum* mosses contain a range of chemical compounds, not found in other plants, that inhibit decomposition (Rydin & Jeglum 2013); whereas woody peats characteristically have higher contents of cutin and lignin than herbaceous peats (Päivänen 1982). The large differences in growth form, substrate quality and production between sedges, *Sphagnum* and trees affect CO_2 cycling and especially CH_4 emissions (Updegraff *et al*. 1998); and it is likely that climate change will alter CO_2 cycling and CH_4 emissions differently in different peatland types (Limpens *et al*. 2008). Therefore, it is important to start differentiating between peatland types if we are to better predict and model changes to these systems.

Northern white-cedar (cedar, *Thuja occidentalis* L.) grows in a variety of habitats including limestone cliffs, sand dunes, riparian systems, abandoned farm fields and peatlands (Johnston 1977, Kost *et al*. 2007). Cedar peatlands are commonly referred to as "cedar swamps" and are typically found in areas with calcium-rich groundwater (Chimner & Hart 1996). Cedar swamps are amongst the most diverse ecosystems of the Great Lakes region of the USA and eastern Canada and provide high-quality wildlife habitat, especially for deer (*Odocoileus virginianus*, Verme 1965). Most inventories of C storage in northern peatlands have been conducted in

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Sphagnum dominated peatlands (Tolonen & Turunen 1996, Yu *et al*. 2003). However, peatlands dominated by *T. occidentalis* are amongst the most common peatland types in the Great Lakes region of the USA and eastern Canada (Heitzman *et al*. 1997, Boulfroy *et al*. 2012). Consequently, the main objectives of this study were to determine: 1) the ages of cedar peatlands; 2) the amount of C stored in the peat profile; and 3) the long-term apparent rate of C accumulation in cedar peatlands in the Great Lakes Region.

METHODS

Site description

We sampled 14 cedar peatland stands, located across northern Minnesota and the Upper Peninsula (UP) of Michigan (USA), during the summers of 2011 and 2012. Cedar peatlands (Figure 1) were identified on the basis of dominance of cedar and the presence of cedar peat (Kost *et al*. 2007, Boulfroy *et al*. 2012). The coring locations were chosen at random, but were all at least 20 m away from the nearest boundary

Figure 1. Photographs of a representative cedar swamp showing typical hummock and pool topography (above) and representative cedar peat in a Russian peat corer (below). Bottom photo shows the lower end of a core, with clearly visible wood chunks in the peat lying on top of mineral sediments.

between cedar peatland and upland. Given that cedar peatland typically occurs in large tracts and often grades into other peatland types, we did not attempt to quantify basin morphology or to calculate peatland-scale carbon storage for this study.

Two peat cores were collected from each site, within 1 m of each other. A tile probe (a series of connecting rods) was used prior to coring to estimate peat thickness and help us to avoid hitting large woody debris. Because coring was made difficult by the high density of roots near the surface, we collected the top 50 cm of peat by cutting with a long serrated knife then gently inserting a 10.16 cm diameter PVC tube over the sample. The PVC tube was lifted from below to minimise compaction and loss of peat. Peat below 50 cm was cored with a Russian peat corer (Aquatic Research Instruments, Hope, Idaho, USA) in 50 cm increments (Figure 1). The cores were stored in 50 cm long sections of 5.08 cm diameter PVC pipe that had been cut lengthwise, and the open sides and the ends were covered by wrapping in plastic film secured with duct tape. After transport to the Wetlands Laboratory at Michigan Technological University (MTU), the samples were immediately frozen (-23 °C, -10 °F) until further analysis. The specific conductivity and pH of soil water were measured in the excavated coring hole using a YSI63 meter (YSI Incorporated, Yellow Springs, Ohio, USA).

Laboratory Methods

We cut the frozen peat cores into 5 cm sections for subsequent analysis. Samples were then oven dried at 110 °C to constant mass (~ 24 hours) (Chambers *et al*. 2011). Volume was calculated using the internal dimensions of the corers. The large surface cores were cut in half lengthwise, and an adjusted volume was calculated accordingly. Bulk density was calculated by dividing oven-dry mass by volume of the sample (Chambers *et al*. 2011).

The 5 cm sections were divided into two subsections. One subsection was placed in a muffle oven at the Michigan Tech Soils Laboratory to determine loss on ignition (LOI) (Chambers *et al*. 2011). Pre- and post-burn masses were measured and ash-free LOI was calculated (post-burn mass subtracted from pre-burn mass = LOI). Percent organic matter (OM) was calculated from LOI. The other subsection was ground and homogenised using a Spex Certi-Prep Mixer/Mill for 15 to 45 seconds. A subset of 98 samples were analysed for % C content using a Shimadzu TOC-5000 Total Organic Carbon Analyser. A regression of % OM to % C was then used to derive % C for all remaining samples. The linear relationship is expressed by the equation

$$y = 0.4371x + 5.5568 \qquad (r^2 = 0.78) \qquad [1]$$

with the independent variable (x) being % OM and the dependent variable (y) being % C.

Long-term apparent rates of C accumulation (LARCA) were calculated using basal ages (date of initiation). Care was taken to select peat samples adjacent to the mineral substratum layer at the bottom of the core, which were sent to Beta Analytic in Miami, FL for ^{14}C dating and calibrated to calendar dates (cal. yr. BP, BP = 1950) (Stuiver *et al*. 1998). LARCA was calculated as total peat C divided by basal age (Tolonen & Turunen 1996, Clymo & Turunen 1998).

RESULTS

For groundwater, mean pH ranged from 5.9 to 6.9 with an average of 6.4; and specific conductivity ranged from 23 and 394 µS cm^{-1}, averaging 179 µS cm^{-1} (SD = 29) (Table 1). Peat thickness ranged from a low of 0.4 m to a high of 3.25 m and averaged 1.12 m (SD = 0.21, Table 1). Rates of vertical increase in peat thickness averaged 0.25 mm yr^{-1} (Table 2).

Across all sites and depths, bulk density averaged 0.19 g cm^{-3} (Table 2); but it varied with depth and between sites. Bulk density was lowest in the uppermost 20 cm (0.13 g cm^{-3}) and increased to an average of 0.17 g cm^{-3} below 20 cm depth (Figure 2). The C content of the peat had a narrow range of 38–43 % across sites and depths, and a mean value of 40.7 % (Table 2). Total C per core ranged from 25 kg m^{-2} to 190 kg m^{-2}, average 77 kg m^{-2} (Table 2).

Basal dates indicate that these cedar sites initiated between 1,910 and 8,590 cal. yr. BP (Table 1). LARCA ranged from a low of 6.4 g m^{-2} yr^{-1} to a high of 39.7 g m^{-2} yr^{-1} and averaged 17.5 g m^{-2} yr^{-1} across all sites (Table 2). Older sites tended to be deeper than younger sites, but the correlation was not strong and some older sites were shallower than younger sites (Figure 3). There was also little correlation between initiation age and LARCA, with older sites accumulating as much C as many younger sites (Figure 3). However, there was a strong correlation between peat thickness and C storage (Figure 4).

DISCUSSION

Age of cedar swamps

Our results indicate that cedar swamps are stable ecosystems that can create woody peat for thousands of years. We observed continuous cedar peat

Table 1. Site physical characteristics, Beta Anayltic laboratory number (ID#), $^{13}C/^{12}C$ quotient ($\delta^{13}C$), radiocarbon age (^{14}C age), median 2 Sigma range, and calibrated age of basal date of peat. Specific conductivity and pH were obtained from groundwater at the site, peat thickness at the coring location, location of site by state and co-ordinates.

Site	ID#	$\delta^{13}C$	^{14}C age (Cal BP)	Calibrated age (yrs BP)	median -2σ	median +2σ	pH	Specific conductivity (μS cm^{-1})	Peat thickness (m)	State	Co-ordinates N	E
Eagle Harbor 1	305347	-26.8	2460±30	2650	2360	2710	6.0	158	1.50	MI	47° 27' 09.1800",	-088° 09' 04.5000"
Eagle Harbor 2	305349	-27.2	2880±30	2990	2930	3080	6.6	23	1.50	MI	47° 27' 04.8600",	-088° 09' 06.3600"
Marsin	305348	-26.2	5880±40	6680	6640	6790	6.4	180	0.50	MI	47° 11' 00.1200",	-088° 38' 33.5400"
Christmas	305353	-25.7	2880±30	2990	2930	3080	6.0	136	0.40	MI	46° 26' 00.1800",	-086° 40' 57.7800"
Bob's Lake 1	305350	-22.5	5100±40	5900	5740	5920	6.8	394	0.50	MI	46° 12' 36.8400",	-087° 30' 35.1000"
Bob's Lake 2	331078	-25.3	7030±40	7900	7790	7950			3.25	MI	46° 12' 37.6000",	-087° 30' 30.2000"
Chassell	331076	-27.0	3800±40	4210	4080	4350	5.9	62	0.90	MI	46° 57' 43.1400",	-088° 28' 00.6600"
Sleeper Lake	331077	-27.6	7790±40	8590	8460	8630	6.6	223	0.90	MI	46° 34' 13.2600",	-085° 34' 48.5100"
Oldman Rd.	331079	-25.9	1970±30	1910	1870	1990	6.9	161	0.40	MN	48° 04'34.1400",	-094° 26'43.0200"
Hwy 71							6.0	108	1.45	MN	48° 01'29.1600",	-094° 02'35.9400"
Shingleton 1							6.4	310	0.95	MI	46° 22' 35.9400",	-086° 26' 31.0200"
Shingleton 2	331080	-21.3	3700±30	4040	3970	4100	6.7		0.95	MI	46° 22' 42.2400",	-086° 26' 27.2400"
Hwy 133	331081	-25.4	6760±40	7610	7570	7670	6.0	229	1.95	MN	47° 04' 15.6600",	-092° 37' 53.8800"
Boomer Rd.							6.9	166	0.60	MN	47° 11' 20.2800",	-091° 41' 01.8600"
Average		-25.5	4568	5043	4940	5115	6.4	179	112.50			
Standard Error		0.6	614	716	718	712	1.0	29	21			

Table 2. Average peat characteristics of cedar swamps. Carbon content and bulk density are averaged throughout each profile. Peat height growth and long-term apparent carbon accumulation rate (LARCA) are calculated from basal dates.

Site	Carbon content (%)	Bulk density (g cm^{-3})	Total carbon (kg C m^{-2})	Height growth (mm yr^{-1})	LARCA (g C m^{-2} yr^{-1})
Eagle Harbor 1	40.7	0.22	105.1	0.57	39.7
Eagle Harbor 2	43.3	0.16	103.2	0.50	34.5
Marsin	36.3	0.38	55.4	0.07	8.3
Christmas	39.1	0.19	28.7	0.13	9.6
Bob's Lake 1	40.5	0.28	56.3	0.08	9.5
Bob's Lake 2	40.3	0.15	189.2	0.41	24.0
Chassell	40.9	0.13	48.1	0.21	11.4
Sleeper Lake	41.2	0.15	55.2	0.10	6.4
Oldman Rd.	39.9	0.16	25.0	0.21	13.1
Hwy 71	43.3	0.14	88.1		
Shingleton 1	42.6	0.17	68.6		
Shingleton 2	36.7	0.20	70.2	0.24	17.4
Hwy 133	43.1	0.18	141.6	0.26	18.6
Boomer Rd.	42.5	0.17	40.5		
Average	40.7	0.19	76.9	0.25	17.5
Standard Error	0.60	0.02	12.2	0.05	3.3

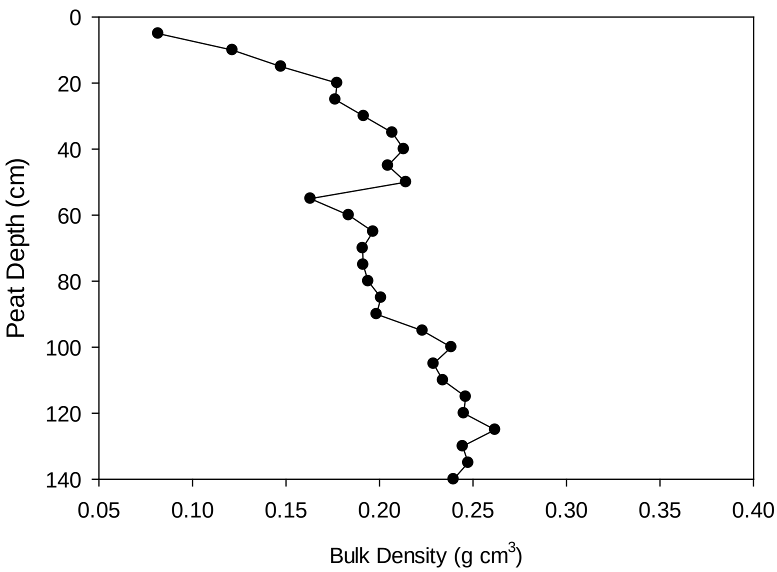

Figure 2. Bulk density profile in the top 140 cm averaged across all sites (14 cores).

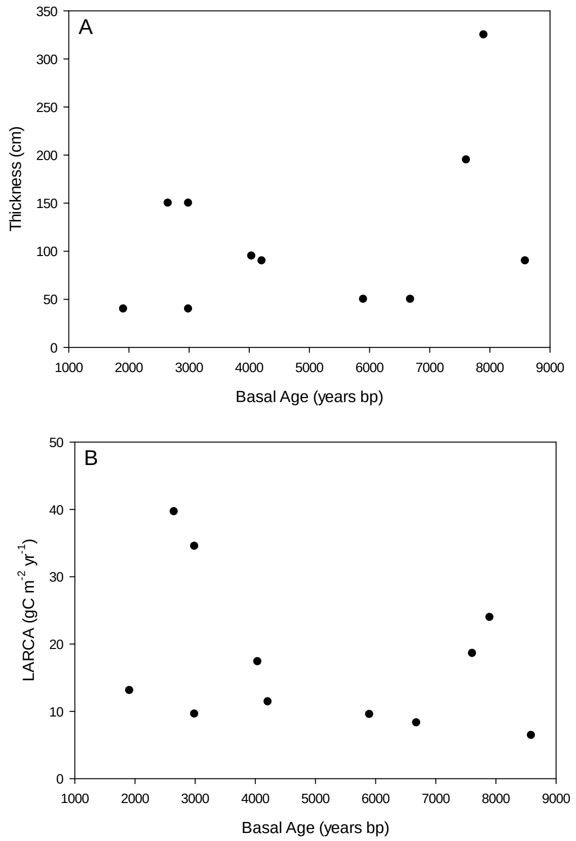

Figure 3. Plots of (A) peat thickness and (B) LARCA against cedar swamp basal age.

throughout all the cores (cedar peat has a distinctive colour and texture that is easily distinguishable).

Cedar has several traits that allow it to be the dominant peat producing plant in these ecosystems. It is the longest-living tree species (up to 400 years) in peatlands in this region (Boulfroy *et al*. 2012). All other trees that commonly occur in cedar swamps (e.g., *Abies balsamea* L., *Larix laricina* (Du Roi) K. Koch, *Fraxinus nigra* Marshall) are much shorter-lived species that die out leaving cedar as the dominant overstorey species (Boulfroy *et al*. 2012). Many late successional species have difficulty regenerating in their own shade; however, cedar regenerates readily in shady conditions. Most cedar reproduction in swamps has been attributed to vegetative layering (Curtis 1946, Nelson 1951), although cedar can also reproduce from seed under favourable light and hydrological conditions (Chimner & Hart 1996, Kost *et al*. 2007). Young cedar trees are shade tolerant and can exist in the understorey for years to decades, growing very slowly - they can take 20 years to reach one metre tall in shade (Johnston 1977). Also, cedar wood is rot-resistant and decays very slowly (Boulfroy *et al*. 2012), which may assist in peat formation.

The initiation of cedar swamps has been continuous since the continental glaciers receded (11,000 to ~8,500 BP; Derouin *et al*. 2007). Areas adjacent to Lake Superior became exposed as water levels dropped to their current positions during the period 4,000 to 2,100 cal. yr. BP (Johnston *et al*. 2004), and some of the newly exposed land became wetlands and peatlands. Our coastal cedar sites (Eagle Harbor and Christmas) had peat initiation dates ranging from 2,880 to 2,460 cal. yr. BP. Basal dating of three nearby *Sphagnum* dominated coastal peatlands in the Western UP showed that these peatlands were also initiated between 2,570 and 1,830 cal. yr. BP (Boisvert 2009). It appears that cedar sites formed in exposed coastal areas which had higher groundwater pH, whereas *Sphagnum* dominated communities formed directly on top of exposed beach sand with lower pH values (Boisvert 2009).

Our non-coastal cedar peatlands had basal peat dates that ranged from 8,590 yr BP to 1,910 yr BP. It is likely that most of these sites were formed from sedge fens after conditions became dry enough for cedar establishment (Glaser 1987). This is supported by our core data, as most of these sites had a thin basal layer of sedge peat underlying the cedar peat. It has been suggested that cedar swamps can overtake sedge fens, but the exact mechanisms are unknown (Cushing 1963, Heinselman 1963). Based on recent studies of the reproductive success of cedar in swamps, cedar encroachment on a sedge fen may only be possible if there are drier areas within the fen to provide more aerobic conditions (Chimner & Hart 1996). Other possible methods of encroachment could involve wind-thrown cedar from outside the fen falling into the fen and vegetatively sprouting from branches (Curtis 1946).

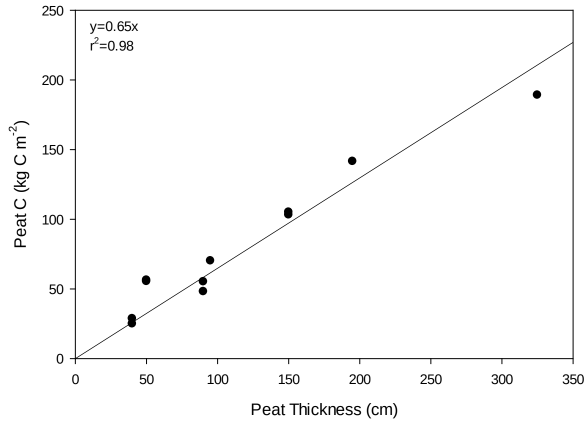

Figure 4. The relationship between total carbon storage of cedar swamps and peat thickness.

Long-term carbon accumulation of cedar peat

The cedar swamps we sampled were located on common soil types for cedar swamps, including: Carbondale, Tawas, Lupton and Cathro mucks (Boulfroy *et al*. 2012). The thickness of the peat layer averaged just over 1 m, with a maximum depth of 3.25 m. In contrast, peat thickness at *Sphagnum* peatlands in the region averages ~3.5 m (Gorham *et al*. 2003, Limpens *et al*. 2008, Chimner *et al*. 2014). However, cedar peatlands have much denser peat (0.16 g cm^{-3}) than *Sphagnum* peatlands (~0.10 g cm^{-3}) (Yu *et al*. 2003, Chimner *et al*. 2014); so even though cedar peatlands are shallower, they hold only slightly smaller quantities of C than *Sphagnum* peat (Chimner *et al*. 2014).

Cedar swamps had on average ~80 kg C m^{-2} stored as peat, which does not include above-ground biomass. Upland forest stands store 67–88 Mg C ha^{-1} above ground with an additional 5–19 Mg C ha^{-1} in standing and fallen woody debris (Weishampel *et al*. 2009). Live biomass in cedar stands is similar to that in upland forests, but with much greater amounts of standing and fallen woody debris. If the maximum values from upland forests (Weishampel *et al*. 2009) were applied to cedar swamps, they would have 800 Mg C ha^{-1} plus 88 Mg C ha^{-1} of live biomass and 19 Mg C ha^{-1} of dead woody debris, so we estimate that they can store roughly 900 Mg C ha^{-1} in total.

Sphagnum peatlands in the northern latitudes of North America have been found to have an average LARCA between 25 and 30 g C m^{-2} yr^{-1} (van Bellen *et al*. 2011). *Sphagnum* peatlands in Finland have been found to have similar LARCAs of 17–19 g C m^{-2} yr^{-1} (Turunen & Moore 2003). These values for *Sphagnum* peatlands are similar to our measured values for cedar swamps, which had an average LARCA of 17.5 g C m^{-2} yr^{-1}.

Peatlands that create woody peat have been insufficiently studied in the temperate and boreal regions. However, peat swamps have become a focus of intense study in tropical regions, where most peat is formed from trees (Chimner & Ewel 2005). Tropical forested peatlands have been shown to store large quantities of C in Indonesia (~2700 Mg C ha^{-1}) and the Amazon Basin (~1500 Mg C ha^{-1}) (Page *et al*. 2011, Lähteenoja *et al*. 2012, Draper *et al*. 2014). These C pools are much larger than those measured in this study (~800 Mg C ha^{-1}), due to the much greater peat thickness and C content found in the tropics. For instance, average peat thickness is approximately 5 m in Indonesia (Jaenicke *et al*. 2008, Page *et al*. 2011) and 2.5 m in Peru (Lähteenoja *et al*. 2009a, Draper *et al*. 2014), whereas it is just over 1 m in our USA sites according to this study. The average % C content of tropical swamp peat also appears to be greater, with average values of 49.5 % in Indonesia (Warren *et al*. 2012) and 46 % in Peru (Lähteenoja *et al*. 2009a), compared to the 41 % for temperate cedar peat determined in this study. However, cedar peat appears to be denser, with an average bulk density of 0.19 g cm^{-3}, compared to average bulk densities of 0.13 g cm^{-3} in Indonesia (Warren *et al*. 2012) and 0.07 g cm^{-3} in Peru (Lähteenoja *et al*. 2009a,b). Tropical swamps also accumulated C faster than our temperate swamps, which had an average LARCA of 20.5 g C m^{-2} yr^{-1}. Peatlands in the Amazon had a mean long-term accumulation rate of 2.2 mm yr^{-1} and a LARCA of 66 g C m^{-2} yr^{-1} (Lahteenoja *et al*. 2009a), while forested tropical peatlands in Indonesia have been found to grow at rates as high as 20 mm yr^{-1} with average values for accumulation rate of 8 mm yr^{-1} and for LARCA of 56 g C m^{-2} yr^{-1} (Page *et al*. 2004).

In conclusion, we found that cedar peatlands could be a major long-term sink of C in the Great Lakes Region. There is currently no regional estimate of the area of cedar peatland in the landscape from which we could calculate a C pool, but cedar swamp peat is likely to be a regionally important C pool given its density and coverage. This study was not designed to quantify cedar peatland C stocks on a peatland or regional scale. However, using the NRCS web soils database "Web Soil Survey 3.0" and known soils that form cedar peat (Cathro, Tawas, Lupton and Carbondale mucks), we can calculate that there is ~420,000 ha of cedar peat in the Upper Peninsula of Michigan (Web Soil Survey 2013). Multiplying this area by our average C density and thickness measurements, we estimate that there is roughly 0.33 Gt of cedar peat in the Upper Peninsula of Michigan. Given the wide distribution of cedar in Eastern North America, the quantity of C in cedar peat is likely to be several Gt, and thus to represent a regionally important pool of C.

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