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Carbon in the Peatlands in the Great Lakes Region

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CARBON IN THE PEATLANDS OF THE GREAT LAKES REGION OF NORTH AMERICA

By

Cassandra A. Ott

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

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Developing and Evaluating Rapid Methods to Estimate Peat Carbon

Manuscript in Progress

Cassandra Ott developed the project, gathered data, analyzed data, and prepared the manuscript. Rodney Chimner assisted Cassandra Ott in the development of the project, analysis of the data, and preparation of the manuscript. Randall Kolka assisted with the development of the project and the preparation of the manuscript.

Chapter 3

Carbon Accumulation of Temperate Forested Peatlands (Northern White Cedar Swamps) in the Great Lakes Region

Manuscript in Progress

Cassandra Ott developed the project, gathered data, analyzed data, and prepared the manuscript. Rodney Chimner assisted Cassandra Ott in the development of the project, analysis of the data, and preparation of the manuscript.

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As many great thinkers have said, “standing on the shoulders of giants” emphasizes not our own abilities, but the abilities of the people who have helped us. I have been fortunate to have many giants in my life. I would like to thank my husband and field assistant Bryan Ott for being supportive and slogging through the muck with me. I would also like to thank my field assistant and comedic relief, Jace Fritzler, for all of his help braving floods, peat, and insects. Lauren Rusin and Jon Bontrager for all of their help with lab work. A special thanks goes to my office mates and peers for companionship, laughs, and entertainment. You all have made “The Dungeons” a cheerful place. At last, I would like to thank my advisor Rod Chimner for the valuable advice, guidance, and editorial work.

Abstract

Peatlands cover only ~3% of the global land area, but store ~30% of the worlds' soil carbon. There are many different peat types that store different amounts of carbon. Most inventories of carbon storage in northern peatlands have been conducted in the expansive *Sphagnum* dominated peatlands. Although, northern white cedar peatlands (NW cedar, *Thuja occidentalis L.*) are also one of the most common peatland types in the Great Lakes Region, occupying more than 2 million hectares. NW cedar swamps are understudied, due in part to the difficulties in collection methods. General lack of rapid and consistent sampling methods has also contributed in a lack of carbon stock quantification for many peatlands. The main objective of this thesis is to quantify: 1) to evaluate peat sampling methods 2) the amount of C-stored and the rates of long-term carbon accumulation in NW cedar peatlands.

We sampled 38 peatlands separated into four categories (black ash, NW cedar swamp, sedge, and *Sphagnum*) during the summers of 2011/2012 across northern MN and the Upper Peninsula of MI. Basal dates of peat indicate that cedar peatlands were between 1970-7790 years old. Cedar peatlands are generally shallower than *Sphagnum* peat, but due to their higher bulk density, hold similar amounts of carbon with our sites averaging ~800 MgC ha^{-1}. We estimate that NW cedar peatlands store over 1.7 Gt of carbon in the Great Lakes Region. Each of the six methods evaluated had a different level of accuracy and requires varying levels of effort and resources. The depth only method and intermittent sampling method were the most accurate methods of peatland sampling.

Chapter 1 . Thesis Introduction

Peatlands are wetlands in which production rates have exceeded decomposition rates and peat is stored beneath the living vegetation (Clymo 1984, Rydin and Jeglum 2006). Peat is partially decomposed plant material. Peatlands are most common in boreal regions, but can also be found in temperate, tropical, and in montane settings (Jaenicke et al. 2008, Lähteenoja et al. 2009a, Cooper et al. 2011). To be classified as a peatland a minimum peat thickness of 40 cm is needed in the United States, which classifies it as a Histosol. Internationally, peatlands have been defined with a minimum peat thickness of 30 cm (Rydin and Jeglum 2006).

There are two main grouping of peatlands; fen (minerotrophic) peatlands that are groundwater driven as opposed to bog (ombrotrophic) peatlands which receive precipitation as the dominant water source (Table 1.1). In the Great Lakes Region, bog peatlands are commonly *Sphagnum* dominated ecosystems with high acidity. Fen peatlands tend to have plant communities better adapted to higher nutrient levels such as sedges (*Carex spp.*) and northern white cedar (*Thuja occidentalis*). Categorizing peatlands based on water chemistry and vegetation is a common practice throughout wetland science (Rydin and Jeglum 2006).

Plants use carbon dioxide from the atmosphere in photosynthesis. Roughly two thirds of the carbon dioxide that is taken in by photosynthesis is released during cellular respiration (Litton et al. 2007). This means that about one third of carbon is used in cellular maintenance and biomass production. The biomass formed includes sugars, organic fatty acids, amino acids, polysaccharides, proteins, lipids, lignin, celluloses, hemicelluloses, and saturated hydrocarbons. Labile carbon compounds are easily decomposed by microbes when the plant sheds biomass or dies. Decomposed carbon compounds leave the system in the form of CO_2, CH_4, or dissolved organic carbon (DOC). Recalcitrant carbon compounds like lignin are more difficult to decompose and last in the system for a much longer amount of time.

Decomposition rates are highly affected by the microbial community. High water tables create an anoxic zone under the living vegetation. This anoxic zone helps contribute to peat formation by limiting oxygen as an electron acceptor during microbial decomposition. Bacteria were found to dominate mineral rich fens while fungi were found to dominate ombrotropic sites ((Golovchenko et al. 2007) Table 1.1). Factors that affect microbial communities include hydrology and pH. For instance, fungi have a higher tolerance for acidic conditions (Winsborough and Basiliko 2010). Some bacteria are able to degrade lignin but they are limited in their efficiency. Fungi are the dominant lignin decomposers, but cannot handle anoxic conditions. This build up of organic material is composed largely of carbon (~50%).

Most inventories of carbon storage in northern peatlands have been conducted in *Sphagnum* dominated peatlands (Tolonen and Turunen 1996, Yu et al. 2003, Frolking and Roulet 2007). However, peatlands dominated by Northern white cedar (NW cedar, *Thuja occidentalis L.*) are one of the most common peatland types in the northern lake states and eastern Canada, occupying more than 2 million hectares (Boulfroy et al. 2012). NW cedar grows in moist and cool climates in areas that receive large amounts of snow in the winter (Johnston 1990). NW cedar are calceophiles, and are located in areas that receive mineral rich ground water. NW cedar peatlands are considered rich to extremely rich fens based on their high pH, specific conductivity, and calcium levels (Glaser 1987). Treed peatlands in the temperate region are understudied and carbon stocks have not been calculated for them. Carbon accumulation rates and storage information will be useful to organizations like the Forest Inventory and Analysis (FIA)

Peatlands that create woody peat have been largely understudied in the temperate and boreal regions. Much is known about forested peatlands in the boreal region, especially black spruce in *Sphagnum* peatlands. However, black spruce tends to not create woody peat because its carbon inputs are minor compared to *Sphagnum* carbon inputs. The majority of treed peatlands with woody peat are located in the tropics where hundreds of different tree species form peat (Chimner and Ewel 2004, Lähteenoja et al. 2009a, Page and Dalal 2011).These tropical treed peatlands have been shown to store large quantities of carbon in Indonesia (55±10 Gt C) and the Amazon Basin (> 3.1 Gt C) (Page et al. 2004, Lähteenoja et al. 2012). However, treed peatlands that create woody peat are not limited to the tropics and can also be common in temperate/boreal regions. Treed peatlands with woody peat have been found to have different peat chemistry and may behave differently with respect to greenhouse gas emissions and changes to water or temperature.

Currently, there is no consistent method to collect sample peat from a core to estimate carbon storage. There is a large demand from international organizations (e.g., Tropical Wetlands Initiative for Climate Adaption and Mitigation (TWINCAM)) and committees (KYOTO Protocol) to estimate carbon stocks. Chapter 2 will outline six coring methods that may help land management agencies such as the US Forest Service and FIA to more accurately and rapidly assess carbon stocks in temperate peatlands. Due to the unique characteristics including having woody peat, a case study on NW cedar swamps is included in Chapter 3. NW cedar swamps were studied and new information about carbon storage and carbon accumulation rates were explored.

Tables

Table 1.1. A generalization of peatland type, associated pH, vegetation, and dominant microbial community. It should be noted that this is a generalization and more variation than this exists.

Peatland Type	pH	Vegetation	Microbe Communities
Bog	More acidic	Sphagnum	Bacteria
Fen	More neutral	Sedge (Carex spp.), NW Cedar (Thuja occidentalis L.)	Fungi

Chapter 2 . Developing and Evaluating Rapid Methods to Estimate Peat Carbon[1]

Abstract

Peatlands cover only ~3% of the global land area but store ~30% of the world's soil carbon. Peatlands store large amounts of carbon due to deep peat deposits stored underneath the vegetative layer. Currently, Forest Inventory and Analysis (FIA) samples only the top 20 cm of organic soils, and therefore it is missing a large percentage of soil carbon in America's peatland forests. Consequently, better methods need to be implemented to allow the FIA to more accurately estimate soil carbon in forested peatlands. We evaluated several peat sampling methods to improve current inventories. We sampled 38 peatlands sampled across northern MN and the Upper Peninsula of Michigan. We tested six methods: 1) whole core sampling, 2) general depth only method, 3) specific depth only method, 4) partial coring #1, 0-20 cm, 5) partial coring #2, 25-75 cm, and 6) intermittent coring. We used linear regressions and r^2 values to determine the accuracy of each method, comparing all methods to the whole core sampling. We found that using a specific depth only method, which is based on vegetation type is accurate for cedar and ash peatlands, but less accurate for *Sphagnum* and sedge. Partial core sampling a section from 25-75 cm in the peat core yielded an accurate linear relationship with depth and total carbon with an r^2 of 0.93. The intermittent method had an even higher linear relationship with an r^2 of 0.94. Each of these methods has a different level of

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[1] The material contained in this chapter will be submitted for publication.

accuracy and requires varying levels of effort and resources. More work needs to be done to make these methods more applicable to global peatlands.

Introduction

Peatlands occur from the tropics to the boreal regions, occupying ~3% of global land area, and storing ~30% of the world's soil carbon (Gorham 1991, Bridgham et al. 1995, Turunen et al. 2002, Limpens et al. 2008). Peatlands accumulate carbon due to primary production exceeding decomposition and other losses (Clymo 1984). Decomposition rates are slow because anaerobic conditions produced by perennially high water table levels limit oxygen infiltration. In the boreal and temperate regions there is an estimated 200-400 Gt of carbon stored in peatlands (Limpens et al. 2008).

The need to better quantify global soil carbon stocks has led to the US Forest Service and Forest Inventory and Analysis (FIA) want to better estimate carbon stocks of peatlands more accurately. The FIA is part of the research arm of the US Forest Service Research and Development collects information on the status, trends, and condition of America's forests. FIA samples tree cover, volume, and soil C of all forest types, including forested peatlands. There are several forested peatland types in the Great Lakes Region including: sedge (*Carex spp.*) dominated peatlands, *Sphagnum* dominated peatlands, black ash (*Fraxinus nigra M.*) dominated peatlands, and northern white cedar (*Thuja occidentalis L.)* dominated peatlands. Despite the large amount of carbon stored up to several meters deep in these peatlands, they are currently only sampled to 20 cm deep by the FIA (Smith et al. 1996). Therefore, current FIA sampling is missing a large percentage of soil carbon in American's peatland forests. Sampled peat is analyzed for bulk density, percent organic matter, and percent carbon. These properties are used to calculate soil carbon of the entire peat profile for the whole plot. Consequently, better methods need to be implemented to allow the FIA to more accurately estimate soil carbon in forested peatlands.

Peat sampling with the greatest accuracy would require collecting multiple whole cores to the base of the peat profile to calculate the total peat carbon stored. Logistically it is difficult for FIA field crews to collect whole peat cores in the field, transport, and analyze them. This research was designed to evaluate more rapid peat sampling methods that could be incorporated into FIA sampling. We tested six total methods: 1) whole core sampling, 2) general peat depth only, 3) peatland type specific depth only, 4) collecting a 0-20 cm partial peat core, 5) collecting a 25-75 cm partial peat core, and 6) collecting intermittent peat samples from within a core. All rapid methods (2-6) were compared to whole core (1) sampling.

Methods

Peatland Sampling

We sampled 38 peatlands during 2011/2012 across northern MN and the Upper Peninsula of Michigan (Table 2.1). Peatlands were initially divided into 4 main vegetation types for sampling: sedge (*Carex spp.*) (8 sites), *Sphagnum* (12 sites), black ash (*Fraxinus nigra M.*) (4 sites), and northern white cedar (*Thuja occidentalis L.*) (14 sites). Locations for coring were randomly selected within a homogenous area in each peatland. One peat core was collected at each site and transported back to the Wetlands Lab at Michigan Technological University (MTU) for analysis. Specific conductivity and pH of the groundwater was analyzed with a YSI63 (YSI Incorporated, Yellow Springs, Ohio, USA) meter in the coring hole. In certain locations, dry summer weather and low water table levels made it impossible to sample pH and specific conductivity. In these instances, sites were re-sampled during a wetter part of the year to obtain accurate pH and specific conductivity.

To determine peat thickness and avoid large buried woody debris, a tile probe was used prior to sampling. A tile probe is commonly used in agriculture to detect tile lines; and consists of multiple rods can be connected to each other and pushed into the soil. Because of the high density of roots in the top 50 cm that made coring difficult, we collected peat in the top 50 cm by first cutting the peat with a long serrated knife and then gently inserting a 10.16 cm diameter PVC tube over the peat (Hribljan 2012). The PVC tube was then lifted from below to minimize 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. Peat cores were stored in 50 cm long 5.08 cm diameter PVC pipe that had been cut in half. The open half and the ends were wrapped in plastic wrap and secured with duct tape for transport to the Wetlands Lab at MTU where they were immediately frozen (-10°F) until further analysis.

Laboratory Methods

In the lab, sample cores were cut using into 2-5 cm sections for analysis (2 cm sections in 2011 and 5 cm in 2012) using a band saw. All sections were then dried in an oven at 110°C for 24 hrs (Chambers et al. 2011). All volumes were calculated based on the dimensions of the corer used because it was assumed that the interior of the sampling instrument was filled with peat. Large samples were cut in half lengthwise, and volume adjusted accordingly. Bulk density was calculated using the mass of the dried sample divided by the volume of the sample (Chambers et al. 2011).

Samples were broken into two subsections lengthwise. One subsection was placed in a muffle oven at the Michigan Tech Soils Laboratory based on methods by Malterer 1992 to determine mineral-free bulk density and loss on ignition (LOI)(Chambers et al. 2011). Pre and post burn mass were measured and LOI was calculated. Percent organic matter was calculated using the equation in Malterer et al. (1992) and then multiplied by bulk density to calculate ash free bulk density (Chambers et al. 2011). The second subsection was homogenised and ground using a Spex Certi-Prep Mixer/Mill for 15-45seconds. Subsamples were then analyzed for carbon content (%) using a Shimadzu TOC-5000 Total Organic Carbon Analyser.

Rapid Peat Sampling Methods

Rapid peat sampling methods were compared to the whole core sampling method. Depth and carbon density were considered when developing the method to be compared, due to the importance of depth and carbon density in total carbon calculations. Both the general depth only method and the specific depth only method involve sampling the depth of the peatland profile. The general depth only method ignores peatland type and groups all peatlands together, while the specific depth only method includes vegetation type, and vegetation specific carbon density values, in its calculations. One consideration taken into account for this method was determining the top of the profile. For all sphagnum peatlands, the top of the profile was the top of the capitula in a lawn. If lawns could not be found, a mid-point between a hummock and hollow was used. For sedge peatlands, the top of the profile was determined at the point where a flat hand could not easily be pushed down into the peat. For ash and cedar peatlands, the top of the profile was defined at a lawn or a midpoint between hummock and hollow.

The 0-20 cm partial core method was based on the current FIA soil sampling method, but with an additional depth measurement. The 25-75 cm partial core method includes a depth measurement and carbon density measurements. This method was used due to the large carbon density variability above 50 cm and the lesser variability below 50 cm. Collecting the 25-75 cm section would allow for carbon density corrections both above and below 50 cm. The intermittent method was developed for use in Indonesian tropical peatland sampling (Kauffman et al. 2011b, 2011a, Kauffman and Donato 2012). The Tropical Wetlands Initiative for Climate Adaption and Mitigation (TWINCAM) method requires peat subsampling from depths of 5-10 cm, 20-25 cm, 37.5-42.5 cm, 72.5-77.5 cm, 197.5-202.5 cm and then every 3 m past that (e.g., 497.5 - 502.5, 797.5-802.5, etc.). We modified this method based on our sub-sample sections, which were in 5 cm increments. The subsamples 37.5-42.5, 72.5-77.5, and 197.5-202.5 were replaced with sections rounded to the nearest 5 cm.

All sampling techniques (general depth only, specific depth only, 0-20 cm partial core, 25-75 cm partial core, and intermittent core) were compared to whole core sampling which was considered the "most accurate" approach. All of the comparisons were based on a linear regression of the sampling technique as the dependent variable and the whole core value. Accuracy was determined by taking whole core total carbon values from sampling technique estimations, dividing by the whole core value and multiplying by 100 to calculate percent accuracy.

Results

Environmental Parameters and Whole Core Sampling

Specific conductivity and pH of the soil water varied between the different peatland vegetation types (Table 2.2). *Sphagnum* peatlands had lowest pH (3.9) and low specific conductivity (52 $\mu S\ cm^{-1}$), while cedar had the greatest pH (6.4) and specific conductivity (179 $\mu S\ cm^{-1}$ (Table 2.2)). Ash and sedge peatlands had intermediate pH levels (5.8 and 4.7, respectively) and low specific conductivity (39 $\mu S\ cm^{-1}$ and 43 $\mu S\ cm^{-1}$, respectively (Table 2.2)).

Peat thickness from our sampled sites ranged from the peatland minimum of 40 cm to 325 cm. Sedge and ash peatlands had the thinnest peats (< 1 m), followed by cedar swamps, with *Sphagnum* peatlands being the deepest overall (Table 2.2). Bulk density was generally lower in upper peats (0.12 $g\ cm^{-3}$) for *Sphagnum* and sedge peats compared to lower peats (0.15 $g\ cm^{-3}$), whereas, cedar peats were similar with depth (Figure 2.1). Percent C varied little with depth for all vegetation types until it started to grade into mineral material at the bottom (Figure 2.2). *Sphagnum* had the greatest %C, followed by sedge, cedar and ash (Figure 2.2).

Total carbon by depth showed similar patterns to bulk density (Figure 2.3). Average total carbon values varied in the top 50 cm between types but had an overall mean of 4.82 gC cm^{-3}. However, below 50 cm all peat types had similar total carbon with a mean of 5.84 gC cm^{-3}. Carbon density (bulk density*%C) varied between vegetation types (Table 2.2). Cedar peat had the most carbon per volume, followed by ash, sedge and *Sphagnum* was the lowest. Using the total whole coring method, we found that total carbon stored in the peatlands varied from 200 to 1600 MgC ha^{-1} (Table 2.2). Total carbon per core showed that cedar and *Sphagnum* peats had the greatest amount of carbon, while sedge and ash had the lowest (Table 2.2).

Comparisons of Rapid Sampling Methods

We compared five rapid sampling methods to the whole core sampling method to see how accurately they estimated total carbon. The first and simplest method we tested was the general depth only method. To use this method, a peat depth measurement must be made and multiplied by a general average carbon concentration. Using our data, we calculated that the depth * average C concentration had a linear relationship with an r^2 = 0.72 when all peatland types were combined (Figure 2.4). The accuracy of the general depth only method was 85%. However, a more accurate relationship was found in the specific depth only method that uses specific vegetation data. This method was more accurate for ash, cedar, and sphagnum (r^2 =0.96, 0.91, 0.72 respectively) (Figure 2.5a, b,d). The linear relationship for sedge was very low with an r^2 value of 0.01 (Figure 2.5c). Overall, the accuracy for the specific depth only method was higher than the general depth only method with an accuracy of 88% not including sedge data.

The 0-20 cm partial core method resulted in very low correlation (r^2 = 0.56) due to the extremely low bulk density in the upper profiles of peat. The low correlation resulted in a low accuracy of only 64% (Figure 2.6). The intermittent core method resulted in an excellent correlation compared to the whole core sampling (r^2 = 0.94 (Figure 2.8)) with an accuracy of 93%.The method that gave the best results required collection of only the 25-75 cm section and sampling peatland depth. This method resulted in an excellent correlation compared to the whole core sampling (r^2 = 0.93 (Figure 2.7)) with an accuracy of 94%.

Discussion

We tested six peat sampling methods: collecting whole cores, general depth only, specific depth only, 0-20 cm partial core, 25-75 cm partial core, and intermittent peat sampling. Whole core sampling is considered the most accurate method because the entire peat core is collected and processed. Whole core sampling is used extensively for paleoecology or quantifying carbon on a small scale. But collecting whole cores, especially in deep peats, is time consuming and logistically challenging to collect, transport, and process. This is especially true for FIA crews that do not have the resources or personnel to carry and core peatlands across the large areas that they sample.

Depth only methods are the simplest methods because they require minimal sampling equipment and does not require samples to be removed from the field. However, depth only measure are the most inaccurate and prone to sampling errors. One main error that can occur is correctly measuring peat depth. It can be difficult to tell where the bottom of the peat layer is located. Peatlands that are directly over sand are easier to sample accurately (can hear sand “crunch”), while peatlands over heavy clays are more difficult to sample as it is difficult to distinguish between the peat and clay. In these cases, it is easy to probe well into the clay and overestimate the depth of peat. The second main error that can occur in the depth only measurements is that it uses average bulk density measurements to calculate total carbon. We found that when bulk densities were different than average values that estimations were skewed.

Partial core sampling requires more work and equipment than depth only sampling. The 0-20 cm partial core method requires 20 cm of peat to be collected and a depth measurement obtained. This sampling technique relies on accurate depth measurements, with the same issues as the depth only methods. This method does not account for bulk densities at deeper levels within the peat profile. Deeper peats tend to have higher bulk densities which are not accounted for in this method.

The 25-75 cm partial core method requires only 50 cm of peat to be collected from the field and a depth measurement obtained. Samples from partial coring weigh much less, take less time to collect, and are less expensive to analyze than using the whole core or intermittent sampling methods. The 25-75 cm partial coring was found to have the best correlation of all partial core ranges tested, with an r^2 value of 0.93 and a 94% accuracy. Error in this method is due to an inaccurate depth measurement or changes in carbon density below 75 cm. Sometimes there are denser or less dense peat at certain depths (Chimner and Karberg 2008).

Intermittent coring was also found to be accurate compared to whole core methods (Figure 2.8). The benefits of partial coring are changes in peat density are observed, and only small amounts of peat have to be carried out of the field and analyzed. The drawback of the intermittent protocol is that although only collect subsamples of peat are collected from the whole depth, the entire peatland must still be cored, which is dense and deep peats, may take hours. It however may be useful in remote sampling, where the weight of the samples themselves may be a limiting factor.

Recommendations

The most accurate method was whole core sampling, followed by partial core method #2 (25-75 cm), intermittent core method, and specific depth only method (Figure 2.9). A combination of peat coring methods could be implemented to maximize sampling effort and accuracy. FIA samples soils from 12 locations within a plot, with 3 soil samples per sub-plot. It is recommended that the specific depth only method is used at minimum at each subplot, and the average depth calculated is based on these 4 depth measurements. However, this method can give erroneous results if the bulk density is greater than normal. For instance, many peatlands have a high bulk density because they have been partially drained due to disturbance. These sites will be underestimated if using depth only. For increased accuracy, a combination of partial core sampling or intermittent core sampling could be collected at one of the subplots with the depth only method being used at the other subplots. If the site is located near a road, time is not a limiting factor, and equipment is available, a whole core could be collected in one subplot location.

Tables and Figures

Table 2.1. Physical properties, location, and type of all sites. Site name, Vegetation type based on dominant vegetation, State the site was found, Coordinates: degrees minutes seconds, Depth of peat layer (cm).

Site	Vegetation Type	State	Coordinates	Depth (cm)
Bete Grise 1	Sedge	MI	46°22'16.9800", -087°08'42.1200"	85
Bete Grise 3	Sedge	MI	47°22'35.4600", -087°58'45.7800"	65
Sleeper Lake 1	Sedge	MI	46°26'59.3400", -085°28'28.8600"	55
Sleeper Lake 2	Sedge	MI	46°27'03.4800", -085°28'29.5200"	65
Folsom Rd	Sedge	MN	47°40'16.2000", -092°42'57.4800"	90
Table Site 1	Sedge	MN	47°40'21.4800", -092°46'10.6800"	95
Pequaming	Sedge	MI	46°51'21.2400", -088°22'01.8000"	60
Reservoir	Sedge	MN	47°02'27.5400", -092°11'35.6400"	150
Bete Grise 2	*Sphagnum*	MI	47°06'40.0800", -088°35'14.5200"	95
Sleeper Lake 3	*Sphagnum*	MI	46°27'28.6800", -085°27'48.7800"	45
Sleeper Lake 5	*Sphagnum*	MI	46°30'29.1000", -085°36'01.1400"	60
Painsdale 1	*Sphagnum*	MI	47°03'08.7000", -088°42'30.3600"	275
Painsdale 2	*Sphagnum*	MI	47°01'22.3800", -088°43'09.6000"	240
Seney 1	*Sphagnum*	MI	46°11'11.7600", -086°01'15.2400"	95
Seney 2	*Sphagnum*	MI	46°11'27.1200", -086°01'09.1800"	45
Seney 3	*Sphagnum*	MI	46°11'42.9000", -086°01'33.0000"	70
Spider Bog	*Sphagnum*	MN	47°29'51.4800", -093°29'27.6000"	175
Table Site 2	*Sphagnum*	MN	47°40'21.4800", -092°46'07.9800"	325
Clear Lake	*Sphagnum*	WI	45°53'14.5200", -089°38'03.1200"	120
St. Germain	*Sphagnum*	WI	45°52'16.3800", -089°31'51.5400"	50
Sleeper Lake 6	Cedar	MI	46°34'13.2600", -085°34'48.5100"	90
Eagle Harbor 1	Cedar	MI	47°27'09.1800", -088°09'04.5000"	150
Eagle Harbor 2	Cedar	MI	47°27'04.8600", -088°09'06.3600"	150
Marzin	Cedar	MI	47°11'00.1200", -088°38'33.5400"	50
Christmas	Cedar	MI	46°26'00.1800", -086°40'57.7800"	40
Bob's Lake 1	Cedar	MI	46°12'36.8400", -087°30'35.1000"	50
Bob's Lake 2	Cedar	MI	46°12'37.6000", -087°30'30.2000"	325
Chassel 1	Cedar	MI	46°57'43.1400", -088°28'00.6600"	90
Oldman Rd	Cedar	MN	48°04'34.1400", -094°26'43.0200"	40
Hwy 71	Cedar	MN	48°01'29.1600", -094°02'35.9400"	145
Shingleton 1	Cedar	MI	46°22'35.9400", -086°26'31.0200"	95
Shingleton 2	Cedar	MI	46°22'42.2400", -086°26'27.2400"	95
Hwy 133	Cedar	MN	47°04'15.6600", -092°37'53.8800"	195
Boomer Rd	Cedar	MN	47°11'20.2800", -091°41'01.8600"	60
Chassel 2	Ash	MI	46°57'43.1400", -088°28'00.6600"	95
Ottowa NF 1	Ash	MI	46°24'45.3600", -089°42'51.3000"	50
Ottowa NF 2	Ash	MI	46°24'45.3600", -089°42'51.3000"	45
Ottowa NF 3	Ash	MI	46°24'56.7600", -089°42'42.1800"	40

Table 2.2. Average properties of peatland types with standard error in parenthesis: Vegetation type with sample size in parenthesis, pH, Sc: Specific conductivity, Depth of peat layer, Bulk density, Percent carbon, Carbon density = bulk density * %C, Total carbon = carbon density * depth.

Vegetation Type	pH	Sc ($\mu S\ cm^{-1}$)	Depth (cm)	Bulk Density ($g\ cm^{-3}$)	%C	C density ($gC\ cm^{-3}$)	Total Carbon ($MgC\ ha^{-1}$)
Sedge	4.67	43.3	76.3	0.12	42.9	5.15	379
(8)		(6.5)	(5.9)	(0.02)	(1.1)		(59.0)
Sphagnum	3.87	52.0	132.9	0.09	45.8	4.12	616
(12)		(2.7)	(28.2)	(0.01)	(0.5)		(614)
Ash	5.78	39.1	57.5	0.16	38.7	6.19	328
(4)		(3.3)	(12.7)	(0.01)	(1.1)		(137)
Cedar	6.40	179.0	104.6	0.19	40.9	7.77	807
(14)		(29)	(19.8)	(0.02)	(0.4)		(469)

Table 2.3. Methods Tested compared with accuracy (method total carbon estimate – whole core total carbon / whole core total carbon * 100) and efficiency with time, weight, and equipment.

Method Tested	Accuracy	Time Needed	Weight of Samples and Equipment	Equipment needed
General Depth Only	85%	low	low	low
Specific Depth Only	88%	low	low	low
0-20 cm Partial Core	64%	low	low	low
25-75 cm Partial Core	94%	moderate	moderate	moderate
Intermittent Core	93%	high	moderately high	high
Whole Core	100%	high	high	high

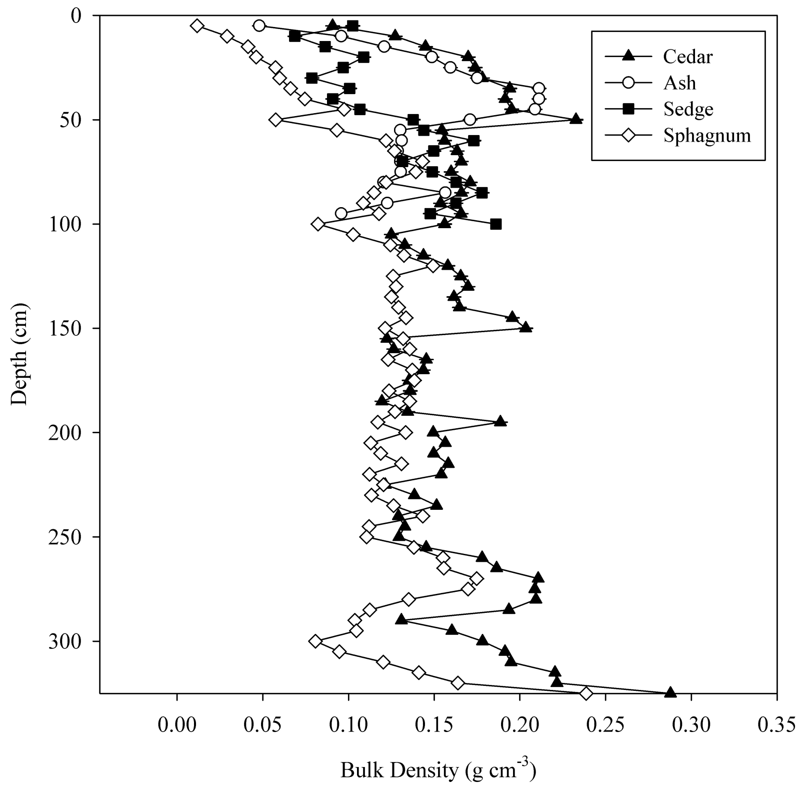

Figure 2.1. Average bulk density by depth of peatland types: bulk density of each subsample plotted with the corresponding depth and separated and averaged by vegetation type.

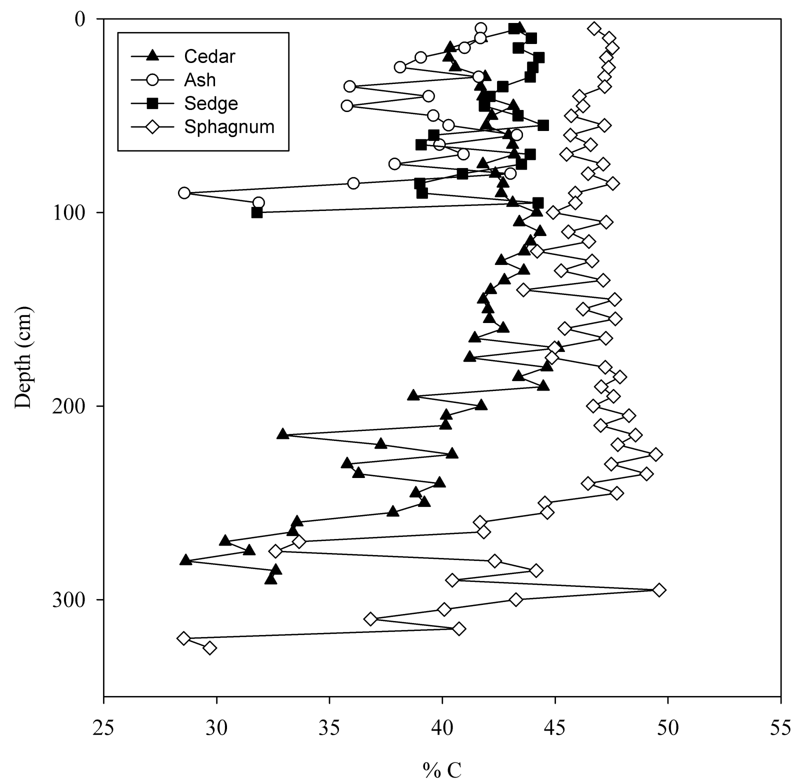

Figure 2.2. Average percent carbon by depth of peatland types: percent carbon plotted with the corresponding depth and separated and averaged by vegetation type.

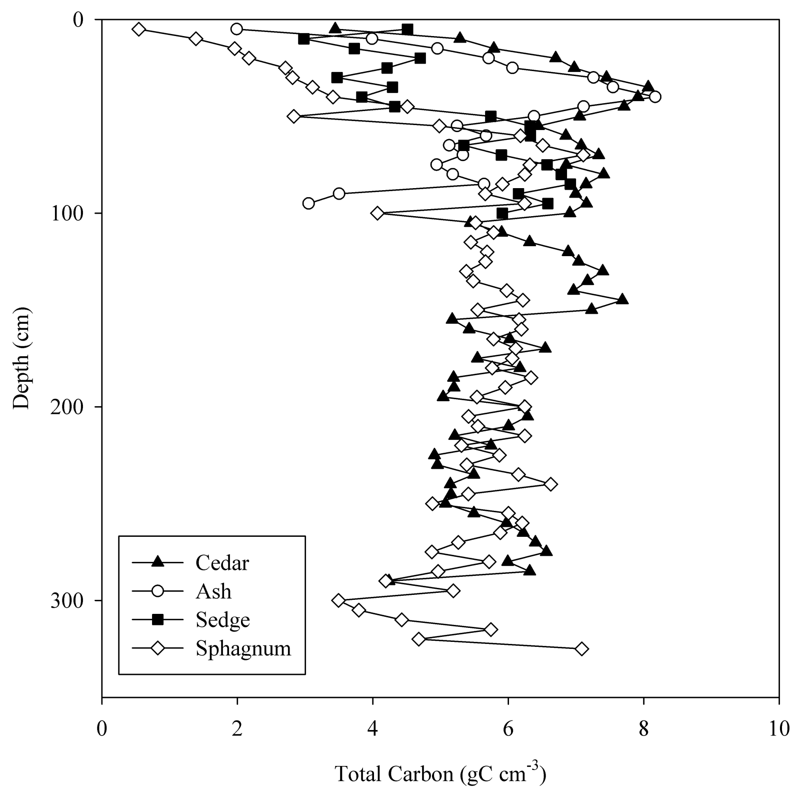

Figure 2.3. Average total carbon by depth of vegetation types: calculated by using average bulk density at depth multiplied by average percent carbon at depth.

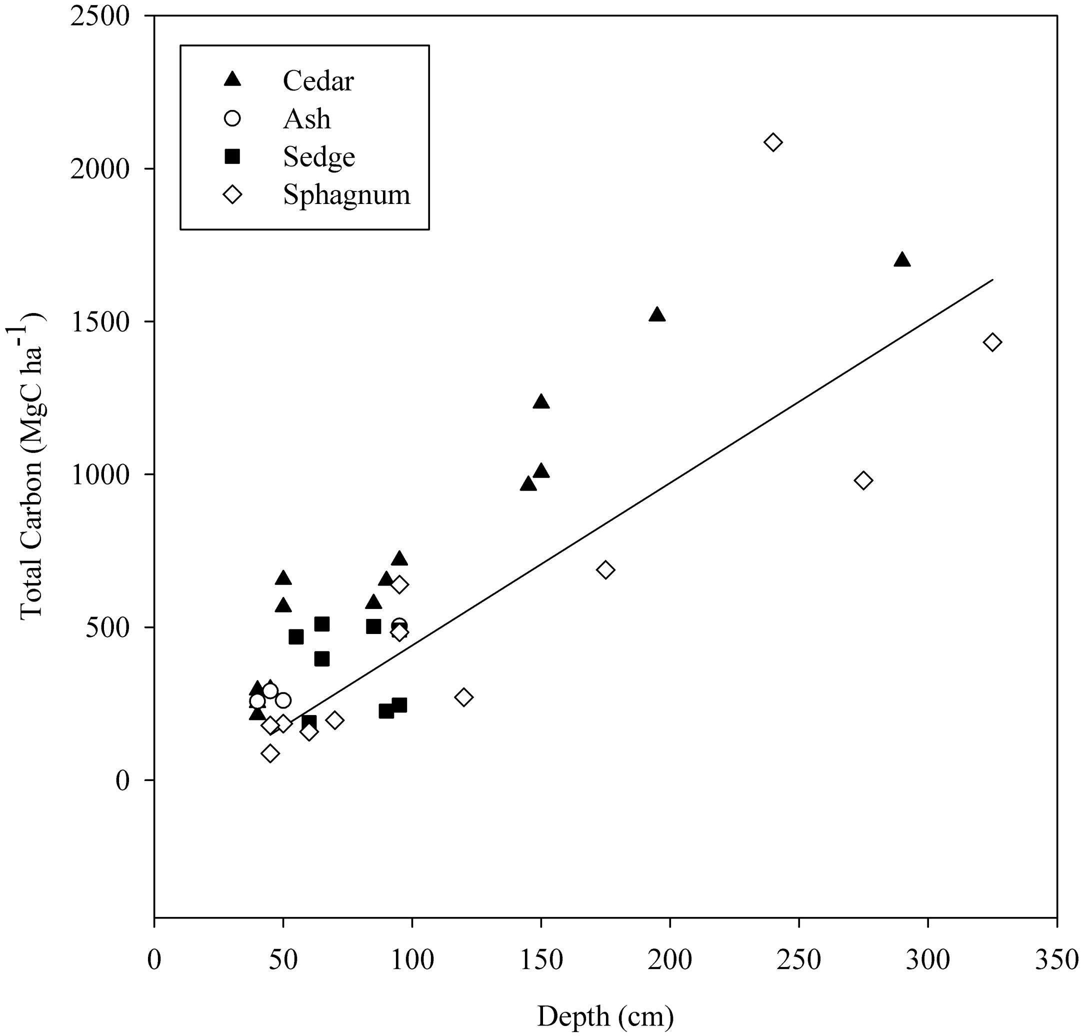

Figure 2.4. General Depth Only Method: linear regression of total carbon per hectare and total depth for all peatland sites (y=5.31x-90.8, r^2=0.72).

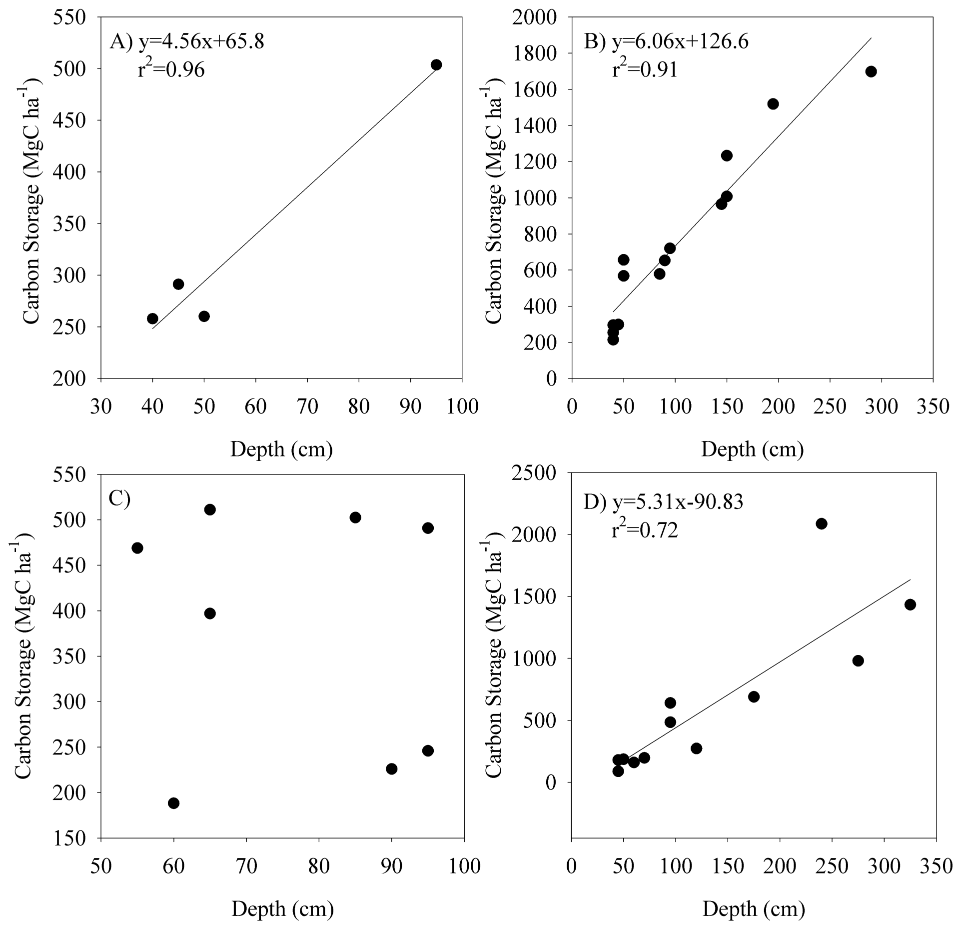

Figure 2.5. Specific Depth Only Method: total carbon storage by depth for each vegetation type, A) Ash, B) Cedar, C) Sedge, D) *Sphagnum*

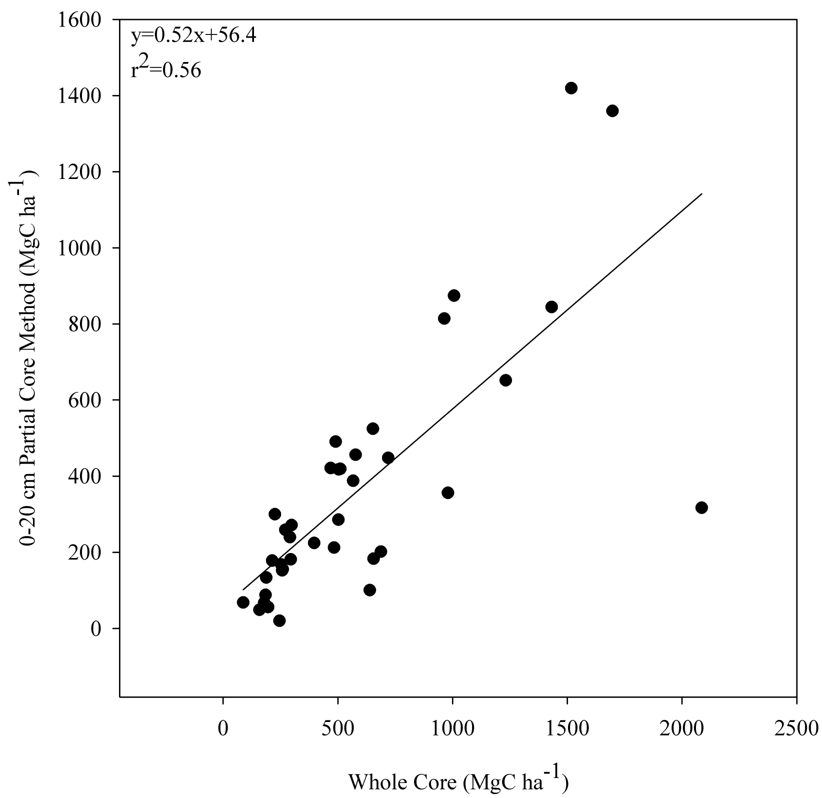

Figure 2.6. Partial Core Sampling Method 0-20 cm: total carbon storage estimate for partial core sampling 0-20 cm compared to total carbon storage of whole core.

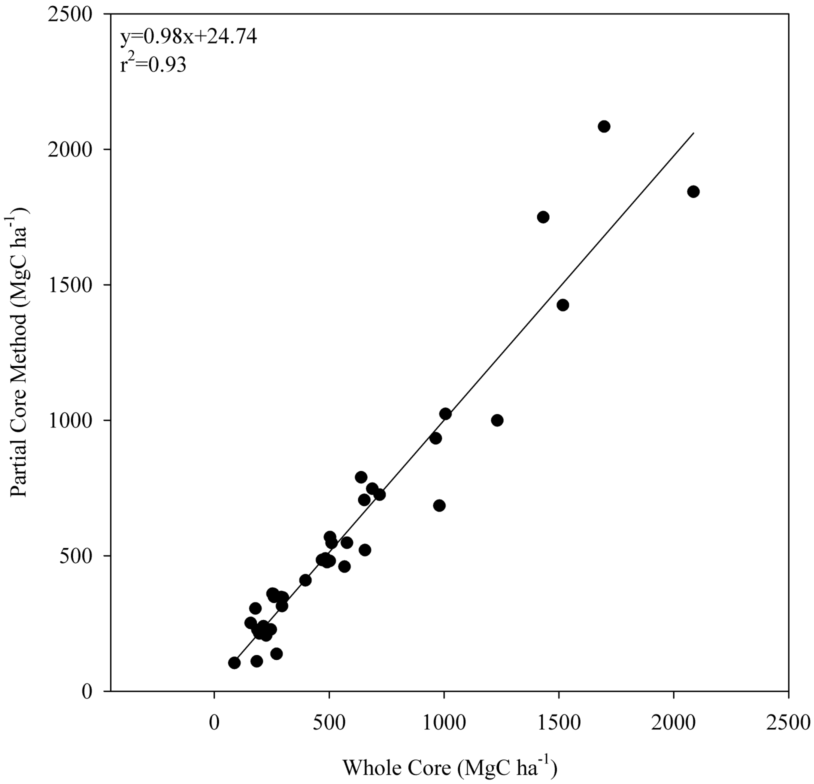

Figure 2.7. Partial Core Sampling Method 25-75 cm: total carbon storage estimate for partial core sampling 25-75 cm compared to total carbon storage of whole core.

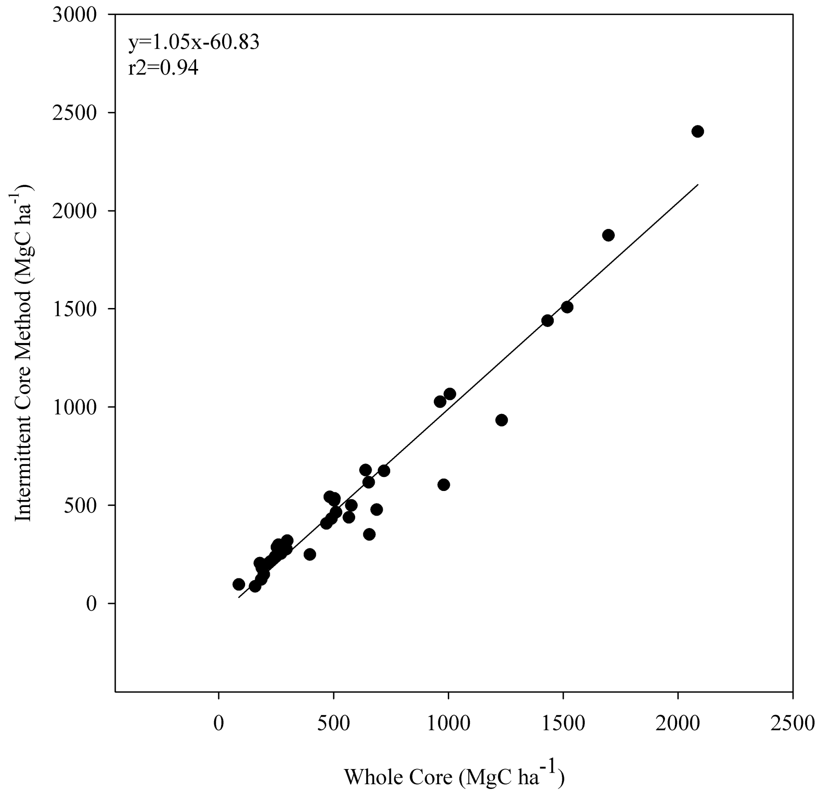

Figure 2.8. Intermittent Core Sampling Method: total carbon storage estimate for the intermittent core method compared to total carbon storage for the whole core method.

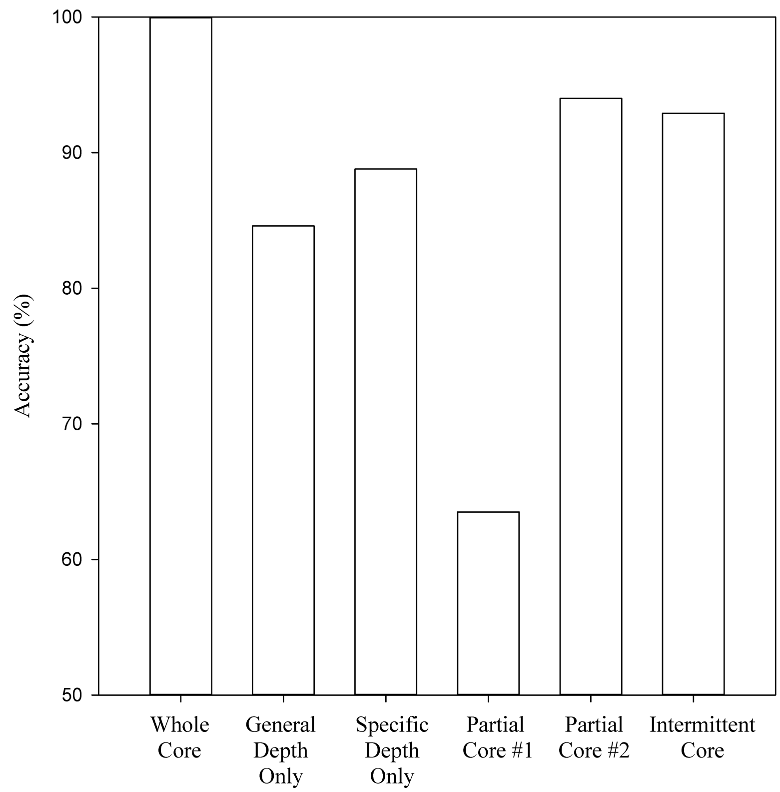

Figure 2.9. Comparing accuracy of rapid assessment techniques with the accuracy level starting at 50: Whole core is considered 100% accurate, General depth only method is 84% accurate, Specific depth only method (excluding sedge) is 88% accurate, Partial core #1 method (0-20cm) is 64% accurate, Partial core #2 (25-75cm) is 94% accurate, and the Intermittent core is 93% accurate (accuracy = total carbon estimate of each method – whole core total carbon / whole core total carbon * 100).

Chapter 3 Carbon Accumulation of Temperate Forested Peatlands (Northern White Cedar Swamps) in the Great Lakes Region[2]

Abstract

Peatlands cover only ~3% of the global land area but store ~30% of the worlds' soil carbon. Most inventories of carbon storage in northern peatlands have been conducted in *Sphagnum* dominated peatlands. However, Northern white cedar peatlands (NW cedar, *Thuja occidentalis L.*) are one of the most common peatland types in the Great Lakes Region, occupying more than 2 million hectares. The main objectives of this study were to quantify: 1) the amount of C-stored and 2) the rates of long-term carbon accumulation in NW cedar peatlands in the Great Lakes Region. We sampled 14 NW cedar peatland sites during the summers of 2011/2012 across northern MN and the Upper Peninsula of MI, USA. Cedar peatlands were found to have an average thickness of 1.12 m. Basal dates indicate that cedar peatlands were initiated between 1970-7790 years ago and were dominated by peat-forming cedar since initiation. Long term apparent carbon accumulation ranged from a low of 7.8 gC m^{-2} yr^{-1} to a high of 54.3 gC m^{-2} yr^{-1}, averaging 20.5 gC m^{-2} yr^{-1}. Cedar peatlands were more shallow than *Sphagnum* peat, but due to their higher bulk density, hold similar amounts of carbon with our sites averaging ~800 MgC ha^{-1} versus 1200 MgC ha^{-1} for *Sphagnum*. We estimate that NW cedar peatlands store over 1.7 Gt of carbon in the Great Lakes Region.

[2] The material contained in this chapter will be submitted for publication.

Introduction

Peatlands are important in the global carbon budget due to their long term storage ability, storing an estimated >600 Gt C since the last glacial maximum (Yu et al. 2010). They store a disproportionate amount of carbon for the land area they cover. For instance, peatlands cover only ~3% of the global land area but store ~30% of the worlds' soil carbon (Gorham 1991). Peatlands accumulate carbon due to primary production exceeding decomposition and other losses (Clymo 1984). Factors such as water table depth, plant community type, and climactic factors all affect the type and amount of peat stored in a peatland (Crum 1988).

Most inventories of carbon storage in northern peatlands have been conducted in *Sphagnum* dominated peatlands (Tolonen and Turunen 1996, Yu et al. 2003, Frolking and Roulet 2007). However, peatlands dominated by Northern white cedar (NW cedar, *Thuja occidentalis L.*) are one of the most common peatland types in the northern lake states of the US and eastern Canada, occupying more than 2 million hectares (Miller n.d., Boulfroy et al. 2012). NW cedar grows in moist and cool climates in areas that receive large amounts of snow in the winter (Johnston 1990). They are considered calciphytes and grow in areas that receive mineral rich ground water, such as rich to extremely rich fens (Chimner and Hart 1996).

Peatlands that create woody peat have been largely understudied in the temperate and boreal regions. The majority of forested peatlands with woody peat are located in the tropics where hundreds of different tree species form peat (Chimner and Ewel 2004, Lähteenoja et al. 2009a, Page and Dalal 2011). These tropical forested peatlands have been shown to store large quantities of carbon in Indonesia (55±10 MgC ha^{-1})and the

Amazon Basin (3.1 MgC ha^{-1}) (Page et al. 2004, Lähteenoja et al. 2012). We wanted to know more about boreal woody peatlands, specifically NW cedar swamps, and how they compare to other peatlands in the same geographical area. To begin to bridge this gap, we quantified the amount of C-stored and the rates of long-term carbon accumulation in NW cedar peatlands in the Great Lakes Region.

Methods

Site Description

We sampled 14 NW cedar peatland stands during the summers of 2011/2012 across northern MN and the Upper Peninsula of MI, USA (Table 3.1). NW cedar peatlands were chosen based on dominance of NW cedar and the presence of NW cedar peat (Kost et al. 2007, Boulfroy et al. 2012). Two peat cores were collected from each site within 1 m of each other. Coring locations were chosen at random. One core was used for analysis and the second core was stored as a backup core. Specific conductivity and pH of the soil water was measured with a YSI63 meter (YSI Incorporated, Yellow Springs, Ohio, USA) from the coring hole.

A tile probe (a series of connecting rods) was used prior to peat coring to avoid hitting large woody debris and to determine peat thickness. Because of the high density of roots in the surface peat that made coring difficult, we collected surface peat in the top 50 cm by first cutting the peat with a long serrated knife and then gently inserting a 10.16 cm diameter PVC tube over the peat (Hribljan 2012). The PVC tube was then lifted from below to minimize 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. Cores were stored in 50 cm long x 5.08 cm diameter PVC that had been cut in half. The open half and the ends were wrapped in plastic wrap and secured with duct tape for transport to the Wetlands lab at Michigan Technological University (MTU). Samples were immediately frozen (-10°F) until further analysis.

Laboratory Methods

We cut frozen peat cores into 5 cm sections for subsequent analysis. Samples were then oven dried at 110°C for 24 hours (Chambers et al. 2011) to find dry mass. Volume was calculated based on the dimensions of the corers with the assumption that the interior of the sampling instrument was filled with peat. The large surface cores were cut in half lengthwise, and an adjusted volume was calculated accordingly. Bulk density was calculated by dividing 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 mineral-free bulk density and loss on ignition (LOI) (Chambers et al. 2011). Pre and post burn mass were measured and ash-free LOI was calculated (Pre burn mass-post burn mass=LOI). Percent organic matter (OM) is calculated from LOI. The other subsection was homogenised and ground using a Spex Certi-Prep Mixer/Mill for 15-45 seconds. Only a subset of samples (98 samples) were analyzed for carbon content (%C) using a Shimadzu TOC-5000 Total Organic Carbon Analyser. A regression of percent organic matter (%OM) to percent carbon (%C) was then used to convert all remaining samples to %C. The linear relationship can be expressed by the equation $y=0.4371x+5.5568$, with the independent variable being %OM and the dependent variable being %C. The r^2 value was 0.78 with a total of 98 samples.

Long term carbon accumulation rates were calculated based on basal ages of NW cedar swamps. Care was taken to select peat samples adjacent to the mineral layer from the bottom of the core without selecting mineral soil. Samples were sent to Beta Analytic in Miami, FL to be ^{14}C dated. Beta Analytic calculated ages were based on known isotope levels and age relationships. These basal ages were combined with the total carbon content to calculate long term apparent carbon accumulation (LARCA) (Clymo and Turunen 1998). LARCA is calculated using weighted average values of carbon density divided by basal ages (Table 3.2) (Tolonen and Turunen 1996, Clymo and Turunen 1998, Page et al. 2004, Lähteenoja et al. 2009b).

Results

Mean pH values of soil water ranged between 5.9 to 6.9 with an average of 6.4 (Table 3.1). Specific conductivity values of soil water ranged between 23-394 $\mu S \cdot cm^{-1}$ and averaged 179 $\mu S \cdot cm^{-1}$ (std=29 (Table 3.1)). Peat thickness ranged from a low of 0.4 m to a high of 3.25 m and averaged 1.12 m (std=0.21 (Table 3.1)). Sites were located on common soil types for cedar peats including Carbondale, Tawas, Lupton, or Cathro mucks (Boulfroy et al. 2012).

Bulk density varied by depth and between sites. Across all sites and depths, bulk density averaged 0.16 g cm^{-3} (std=0.02 (Table 3.2)). Bulk density was lowest in the upper 20 cm (0.13 g cm^{-3}) and increased to an average of (0.17 g cm^{-3}) below 20 cm. Percent carbon had a narrow range between 38-43% across sites and depths with a mean of 41% (std=0.6 (Table 3.2)). Total C per core ranged between 254 MgC ha^{-1} and 1902 MgC ha^{-1}, averaging 807 MgC ha^{-1} (std=122 (Table 3.2)).

Basal dates indicate that these cedar sites initiated between 1970-7790 Cal yr BP (Table 3.1). LARCA ranged from a low of 7.8 gC m^{-2} yr^{-1} to a high of 54.3 gC m^{-2} yr^{-1}. However, most sites ranged between 7.8-27.3 gC m^{-2} yr^{-1} and averaged 20.5 gC m^{-2} yr^{-1} across all sites (Table 3.2). There was a small correlation between initiation age and depth, however, no correlation was seen between initiation age and LARCA, with older sites accumulating as much carbon as newer sites (Figure 3.1).

Discussion

Ages of Cedar Peatlands

Our results indicate that NW cedar swamps are stable ecosystems that can retain cedar for thousands of years. NW cedar peat has a distinctive color and texture that easily distinguishes it from *Sphagnum* and sedge peat. We observed continuous cedar peat found in the cores with peat initiation ages of up to 7790 Cal yr BP. This is the first time that NW cedar has been shown to dominate a peatland for thousands of years, despite probable disturbances over that time frame.

NW cedar has several traits that can allow it to be the dominant peat producing plant in a cedar swamp. It is long-lived compared to other trees in swamp such as balsam fir (*Abies balsamea L.*), black ash (*Fraxinus nigra M.*), and tag alder (*Alnus rugosa*) and can live up to 400 years in swamps (Boulfroy et al. 2012). Northern white cedar is shade tolerant and can reproduce from seed in partly shaded conditions. Young cedar can exist in the understory for many years before a gap disturbance allows them to reach the upper canopy (Boulfroy et al. 2012). It can regenerate after blow down and low frequency fires by asexual, vegetative reproduction. Most reproduction in swamps is thought to be vegetative layering, due to shallow root systems and susceptibility to various butt rot fungi (Kost et al. 2007, Boulfroy et al. 2012). Additionally, cedar germinate readily from seed in proper light and hydrological conditions (Chimner and Hart 1996, Kost et al. 2007). Cedar wood is rot-resistant and decays very slowly (Boulfroy et al. 2012). The slow decay rates of NW cedar likely assist in peat formation in swamps.

NW cedar swamp initiation has been continuous since the glaciers receded. There are two likely pathways that allowed for cedar swamp initiation: coastal swamp initiation and lake in-filling. Our coastal sites (Eagle Harbor and Christmas) established in areas adjacent to Lake Superior became exposed as water levels dropped (4000-2100 Cal yr BP) to its current level (Johnston et al. 2004). Some of the newly exposed land, especially in the wetter areas, became wetlands and peatlands. Our coastal NW cedar sites had peat initiation dates ranging from 2460-2880 Cal yr BP. Basal dating from three nearby *Sphagnum* dominated coastal peatlands in the Western UP found that these peatlands initiated between 2570 and 1830 Cal yr BP (Boisvert 2009). Both Sphagnum dominated peatlands and NW cedar dominated peatlands established along the Lake Superior coastline. It appears that NW cedar sites formed in exposed coastal areas that had higher pH groundwater, which allowed cedar swamps to form directly on top of exposed beach sand instead of *Sphagnum* dominated communities.

Our non-coastal NW cedar peatlands had basal peat dates that ranged from 7000 to 1970 yr BP. The oldest NW cedar sites had basal dates around 7000 Cal yr BP and formed after deglaciation in the region (Yu et al. 2003). The youngest peat initiation date in our study was 1970 Cal yr BP, which is close to the youngest age of peat initiation on the Lake Agassiz Plain (1900 Cal yr BP) (Glaser 1987). Most of these sites were likely formed by an infilling lake and likely established after conditions became dry enough for cedar establishment (Glaser 1987).

Long-term carbon accumulation of cedar peat

Sphagnum and NW cedar peatlands have similar long term average carbon accumulation rates (LARCA). NW cedar peatlands are shallower on average than *Sphagnum* peatlands in the boreal/temperate region. Our NW cedar sites averaged just over 1 m thick, with the maximum depth of over 3 m. In contrast, *Sphagnum* peatlands average ~3.5 m (Gorham et al. 2003, Limpens et al. 2008). However, cedar peatlands have much denser peat (0.16 g cm^{-3}) compared to *Sphagnum* (0.10 g cm^{-3}) (Yu et al. 2003, Ott et al. 2013). So even though NW cedar peatlands are much shallower, they hold only slightly lower amounts of carbon compared to *Sphagnum* peat.

NW cedar swamp peat averages ~800 MgC ha^{-1}, this does not include above ground biomass. Upland forest stands can store 67-88 MgC ha^{-1} above ground with an additional 5-19 MgC ha^{-1} in standing and down woody debris (Weishampel et al. 2009). NW cedar stands have similar live biomass as upland forests, but with much greater amounts of standing and down woody debris. If NW cedar swamps have 800 MgC ha^{-1} plus 88 MgC ha^{-1} of live biomass and 19 MgC ha^{-1} of dead woody debris, they can store over 900 MgC ha^{-1}. *Sphagnum* peatlands in the same region averaged 1286 MgC ha^{-1} (Weishampel et al. 2009). Carbon storage of NW cedar peatlands per hectare is similar to peatlands dominated by different vegetation types in the same region.

Sphagnum peatlands in the northern latitudes of North America have an average LARCA rate of 25-30 gC m^{-2} yr^{-1} (Van Bellen et al. 2011). *Sphagnum* peatlands in Finland have been found to have LARCA rates averaging from 17-19 gC m^{-2} yr^{-1} (Turunen and Moore 2003). Cedar peats have lower LARCA rates (20.5 gC m^{-2} yr^{-1}) than other North American *Sphagnum* peatlands, but are comparable to Finnish *Sphagnum* peatlands. Lower LARCA rates for cedar may be due to the susceptibility of NW cedar swamps to drought and fire or may be due to the slower growth rate of trees (Heitzman et al. 1997, Hofmeyer et al. 2009, Boulfroy et al. 2012).

In the United States and Ontario there are at least 2 million hectares of NW cedar swamps that store at least 1.7Gt of carbon. (Boulfroy et al. 2012). This calculation was based on known NW cedar soils (Cathro, Tawas, Lupton, and Carbondale mucks) in the United States (Miller n.d.) as well as an estimate of NW cedar swamp cover from Boulfroy et al. (2012).Using our average carbon density measurements, we multiplied the total number of hectares by the average carbon storage of NW cedar swamps per hectare. There are additional NW cedar swamps in Quebec and likely more in the North Eastern US with different soil types that were not included in this calculation due to a lack of information.

In conclusion, Northern white cedar peatlands have dominated the Great Lakes Region for a few thousand years, storing carbon at a long term average rate of 20.5 gC m^{-}

^{2} yr^{-1}. These swamps store ~800 MgC ha^{-1} with a minimum estimated total of 1.7 Gt of stored carbon across the United States and Canada. NW cedar peatlands are a temperate example of treed peatlands storing similar amounts of carbon at similar rates as other peatland types in the same region.

Tables and Figures

Table 3.1 NW cedar swamp site physical characteristics: Site name, basal initiation date (Cal yr BP), pH, SC=Specific conductivity (µS cm^{-1}), Depth of peat (m), location by State, Coordinates in degrees, minutes, seconds.

Site	Basal Initiation Date (Cal yr BP)	pH	Specific Conductivity (µS cm^{-1})	Depth (m)	State	Coordinates (Degrees Minutes Seconds)
Eagle Harbor 1	2460±30	6.0	158	1.50	MI	47°27'09.1800", -088°09'04.5000"
Eagle Harbor 2	2880±30	6.6	23	1.50	MI	47°27'04.8600", -088°09'06.3600"
Marsin	5880±40	6.4	180	0.50	MI	47°11'00.1200", -088°38'33.5400"
Christmas	2880±30	6.0	136	0.40	MI	46°26'00.1800", -086°40'57.7800"
Bob's Lake 1	5100±40	6.8	394	0.50	MI	46°12'36.8400", -087°30'35.1000"
Bob's Lake 2	7030±40			3.25	MI	46°12'37.6000", -087°30'30.2000"
Chassell	3800±40	5.9	62	0.90	MI	46°57'43.1400", -088°28'00.6600"
Sleeper Lake	7790±40	6.6	223	0.90	MI	46°34'13.2600", -085°34'48.5100"
Oldman Rd	1970±30	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	3700±30	6.7		0.95	MI	46°22'42.2400", -086°26'27.2400"
Hwy 133	6760±40	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	4568	6.4	179	112.50		
Standard Error	614	10	29	21		

Table 3.2 NW cedar swamp average peat characteristics: percent carbon throughout profile, bulk density throughout profile, total carbon = bulk density*%C*depth, PAR (peat accumulation rate) = depth/basal age, and LARCA = PAR *bulk density*%C.

Site	Percent Carbon (%)	Bulk Density ($g\ cm^{-3}$)	Total Carbon ($MgC\ ha^{-1}$)	PAR ($mm\ yr^{-1}$)	LARCA ($g\ m^{-2}\ yr^{-1}$)
Eagle Harbor 1	40.74	0.22	1051	0.61	54.86
Eagle Harbor 2	43.25	0.16	1032	0.52	35.88
Marsin	36.26	0.38	554	0.09	11.77
Christmas	39.12	0.19	287	0.14	10.15
Bob's Lake 1	40.47	0.28	563	0.10	11.11
Bob's Lake 2	40.31	0.15	1892	0.46	27.19
Chassell	40.89	0.13	481	0.24	12.68
Sleeper Lake	41.16	0.15	552	0.12	7.11
Oldman Rd	39.91	0.16	250	0.23	12.95
Hwy 71	43.33	0.14	881		
Shingleton 1	42.61	0.17	686		
Shingleton 2	36.73	0.20	702	0.26	18.99
Hwy 133	43.13	0.18	1416	0.29	21.06
Boomer Rd	42.50	0.17	405		
Average	40.74	0.19	768	0.27	20.32
Standard Error	0.60	0.02	122	615	615

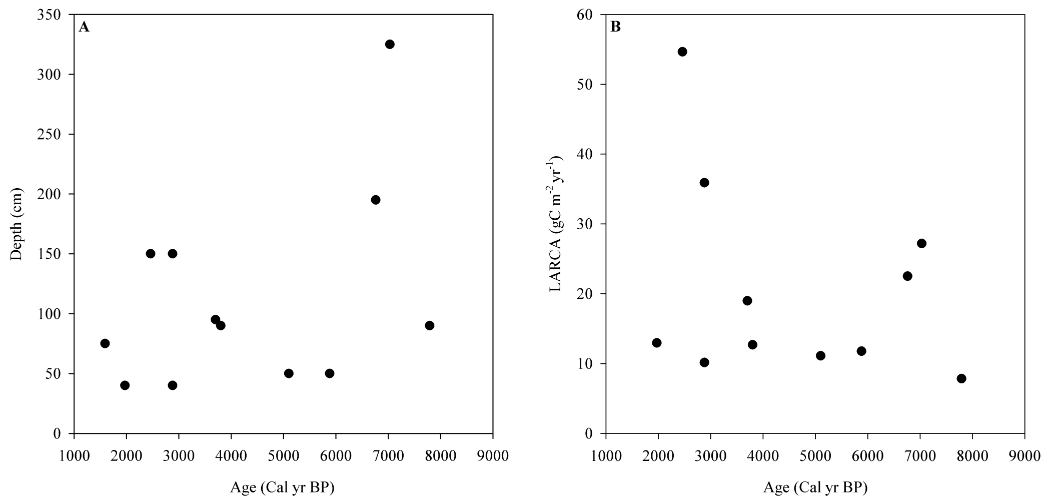

Figure 3.1 NW cedar swamp basal age compared to A) Depth, B) LARCA.

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