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SHORT COMMUNICATION

Developing and Evaluating Rapid Field Methods to Estimate Peat Carbon

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Abstract Many international protocols (e.g., REDD+) are developing inventories of ecosystem carbon stocks and fluxes at country and regional scales, which can include peatlands. As the only nationally implemented field inventory and re-measurement of forest soils in the US, the USDA Forest Service Forest Inventory and Analysis Program (FIA) samples the top 20 cm of organic soils, but there is a large unsampled fraction of soil carbon stored in America's peatland forests. Improved methods could allow the FIA program to more comprehensively estimate soil carbon stocks and stock change in forested peatlands. We evaluated six rapid peat sampling methods in northern peatlands: 1) general probing of peat thickness, 2) general probing of peat thickness by general vegetation type, 3) partial profile coring #1, 0–20 cm, 4) partial profile coring #2, 25–75 cm, 5) partial profile coring #3, 50–100 cm, 6) intermittent profile coring and compared them to 7) measurements derived from whole profile sampling. We also tested our methods against an independent database of 85 peat cores collected from Manitoba, Canada. Overall, we found that the 0–20 cm partial profile core method was the least accurate method and should not be used (64–67 % accurate). The remaining rapid peat sampling methods all provided accuracies >85 % compared to whole profile sampling. In conclusion, we found that there are several good options for rapidly sampling peat C stocks that if incorporated, could greatly increase our estimates of carbon stored in peat.

Keywords Peat · Coring · Carbon · Sampling · Soil

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Introduction

Globally, peatlands occupy approximately 3 % of global land area, but they store roughly 30 % of the world's soil carbon (C) (Gorham 1991; Bridgham et al. 1995; Turunen et al. 2002; Limpens et al. 2008). In the boreal and temperate regions, peatlands store an estimated 200–400 Gt C (Limpens et al. 2008). However, these estimates of peat C stocks are global estimates with large uncertainties as many nations have incomplete or non-existent peat C inventories.

To improve the C stock estimates, many international protocols (e.g., REDD+) are developing inventories of ecosystem C at country and regional scales, which can include peatlands (Jaenicke et al. 2008; Valpola et al. 2012; Warren et al. 2012). In the United States, the USDA Forest Service Forest Inventory and Analysis Program (FIA) collects information on the status, trends, and condition of forests (public and private) across the United States. FIA inventories tree cover, tree volume, and associated forest health parameters including soil C across all forest types, including forested peatlands (Smith et al. 2009; Woodall et al. 2011). However, FIA samples only the top 20 cm of forest soil, with the exception of Alaska, including those found in forested peatlands (USDA Forest Service 2011).

Sampling peatland C with the greatest accuracy requires collecting multiple whole cores to the base of the peat profile.

Logistically, it is difficult for inventory programs like FIA to collect whole peat cores in the field, transport, and analyze them. Therefore, new peat sampling methods are needed to improve the estimates of soil carbon stocks in peatlands, particularly those generated at the national scale. This research was designed to evaluate rapid peat sampling methods that could be incorporated into national scale inventory efforts, specifically the FIA program. We evaluated six rapid peat sampling methods and compared them to estimates derived from whole profile sampling. After testing relationships with the peat cores we collected, we applied our relationships to a similar but independent data set collected in Manitoba, Canada.

Methods

Peat Coring

We sampled 38 peatlands during 2011/2012 across northern Minnesota and the Upper Peninsula of Michigan. Peatlands were divided into 4 main vegetation types for sampling: sedge dominated understory (*Carex spp.*), *Sphagnum* dominated understory with black spruce (*Picea mariana* Mill.) and/or tamarack (*Larix laricina* Du Roi) over stories, black ash dominated (*Fraxinus nigra* M.) overstory, and northern white-cedar dominated (*Thuja occidentalis* L.) overstory. Locations for coring were randomly selected within a homogenous area in each peatland. The entire peat profile was cored once at each site and transported back to the Wetland Ecology and Restoration Lab at Michigan Technological University (MTU) for analysis. Specific conductivity and pH of the pore water was analyzed with a YSI63 meter (YSI Incorporated, Yellow Springs, Ohio, USA) in the coring hole.

Peat sampling techniques varied by depth within the peat profile. The high density of roots in the top 50 cm made coring difficult, so we collected this peat by first cutting it with a long serrated knife and then gently inserting a 10.16 cm diameter PVC tube through 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 until mineral material was reached. Peat cores were stored in 50 long by 5.08 cm diameter PVC pipe that had been cut in half lengthwise. The open half and the ends were wrapped in plastic wrap and secured with duct tape. All core sections were transported to MTU where they were immediately frozen (−23 °C) until further analysis.

Laboratory Methods

In the lab, frozen sample cores were cut into 5 cm sections for analysis using a band saw then oven dried at 60 °C for 24 h (Chambers et al. 2011). Bulk density was calculated using the mass of the dried sample divided by the volume of the wet sample (Chambers et al. 2011). The peat was then homogenized after large roots (e.g. >2 mm diameter) were removed and ground using a Spex Certi-Prep Mixer/Mill for 15–45 s then analyzed for percent carbon (%C) using a Shimadzu TOC-5000 Total Organic Carbon Analyzer. Carbon mass was calculated for each 5 cm section by multiplying bulk density * 5 cm depth interval * %C. Total carbon stock of each peat core was calculated by summing carbon mass of each 5 cm section along the length of the entire core. Average volumetric carbon density of each core was calculated by dividing total carbon mass by the peat thickness.

Rapid Peat Sampling Methods

We assume collecting %C and bulk density from the entire peat profile is the most accurate method to measure the total mass of peat carbon. We refer to these measurements as whole profile estimates. Several methods of rapid peat sampling (using subsets of the data from the whole profile sampling) were then calculated and compared to the whole profile estimates to see if simpler techniques could generate similar estimates of carbon stocks. We tested several sampling and estimation methods: A) peat probing, subdivided into a thickness-only (Table 1: #1) and a thickness corrected by vegetation estimate (Table 1: #2), B) partial coring using only a subset of peat collected near the surface (three methods tested (Table 1: #3-#5), and C) an intermittent peat sampling method where the entire peat profile is cored, but only a few subsamples of peat are collected for laboratory analysis (Table 1: #6). These methods were tested post-hoc against the estimates derived from the collecting and analyzing the entire peat profile (Table 1: #7).

The probing for thickness involves only measuring the thickness of the peat profile and multiplying it by a general peat carbon density to calculate total carbon mass. The

Table 1 Summary of peat sampling methods evaluated to estimate peat carbon storage

Method tested	Time needed	Weight of samples and equipment	Equipment needed
Peat probing			
1) Probe only	low	low	low
2) Vegetation correction	low	low	low
Partial coring			
3) Collect 0–20 cm	moderate	moderate	moderate
4) Collect 25–75 cm	moderate	moderate	moderate
5) Collect 50–100 cm	moderate	moderate	moderate
6) Intermittent core	high	moderate	high
7) Whole profile	very high	high	high

thickness only method ignores peatland types and uses a general carbon density for all peatland types; the probing by vegetation method uses a different carbon density value for each of the four different major vegetation types.

For the three partial coring methods (0–20, 25–75, and 50–100 cm depths), we only analyzed a subsection of the peat from the top portion (100 cm) of the core. Total carbon mass was then estimated by averaging the carbon density of the partial core (bulk density* depth interval* %C) and multiplying it by the total peat thickness.

The intermittent method that we tested was developed for use in Indonesian peatland sampling (Kauffman et al. 2011a, b; Kauffman and Donato 2012). The intermittent sampling method was developed because many tropical peatlands are very deep (>5 m) and collecting, carrying, and analyzing all the peat was logistically difficult. The method subsamples 5 cm sections of peat in the field from depths of 5–10, 20–25, 37.5–42.5, 72.5–77.5, 197.5–202.5 cm and then every 3 m past that (e.g., 497.5–502.5, 797.5–802.5, etc.) (Kauffman and Donato 2012). We modified this method based on our sub-sample sub-sample sections, which were in 5 cm increments (i.e., 40–45, 70–75, 195–200 cm).

Independent Test of Rapid Sampling Methods

We tested our rapid peat sampling methods against an independent dataset of Canadian peat cores (Zoltai et al. 2000). The Zoltai dataset consists of 640 peat cores, from 426 sites collected between 1970 and 1989 across central and western Canada (Zoltai et al. 2000). We choose to use the cores collected in southern Manitoba (85 cores from 59 sites collected in 1983) because they are the closest geographically to our cores in Michigan and Minnesota. Specific data for each peat core include: wetland type, water chemistry, vegetation composition, total peat thickness, depth of horizon samples, bulk density, von post decomposition class and loss on ignition (LOI). We used the average LOI to %C content conversion (LOI*0.52 = %C) as calculated for Canadian peats (Bhatti and Bauer 2002) to covert LOI to %C. To test for thickness by vegetation methodology (#2, Table 1), we stratified the peat cores by wetland type. Average carbon densities were then applied from Michigan and Minnesota to the Manitoba cores. Because the Zoltai cores were sampled with varying horizons thicknesses and not in 0–5 cm increments, we had to use the closest horizons to calculate C density in this test.

Results

Whole Profile Sampling from MI/MN

Peatlands sampled had a large range of pH, specific conductivity, and peat thickness (Table 2). Average bulk density for the whole peat cores ranged between 0.09 and 0.19 and average %C ranged between 39 and 46 %. Average total carbon content varied in the top 60 cm between types and had an overall mean of 4.8 gC cm^{-3} (Fig. 1), below 60 cm all peat types had similar total carbon content with a mean of 5.8 gC cm^{-3}. Peat carbon density varied between 4.33 and 6.65 gC cm^{-3} and total carbon stocks varied between 200 and 1,600 MgC ha^{-1} (Table 2).

Comparisons of Rapid Sampling Methods for Estimating Peat C Stocks

Averaging across all peatland types, rapid sampling methods detected 67 to 115 % (<100 % is an underestimate and >100 % is an overestimate compared to whole profile sampling) of total peat carbon identified using the whole profile method (Table 3). Partial core sampling of 0–20 cm had the poorest relative accuracy at only 67 % across all vegetation types. The partial core from 0 to 20 cm method had better predictive capacity in the cedar peatlands and worked poorest in the *Sphagnum* peatlands. The two other partial coring methods (25–75, 50–100 cm) gave better results averaging 105 and 115 % of whole core C, respectively, across all vegetation types. The partial cores had the greatest predictive ability in the cedar and *Sphagnum* soils. The intermittent sampling method had an average relative accuracy of 95 %, working equally well across vegetation types.

The methods relying upon measurements of peat thickness performed quite well. The thickness only method, which just takes the thickness of the peat and multiplies it by the average carbon density of organic soil (5.57 gC cm^{-3}; Table 2), averaged 114 % of whole profile C (Table 3). If a vegetation specific carbon density is applied as a correction factor (thickness*carbon density by vegetation type: Table 2), the relative accuracy improved to 110 %.

Independent Test of Rapid Sampling Methods

We tested our rapid sampling methods on 63 peat cores collected from southern Manitoba (Zoltai et al. 2000). The poorest method tested was again the 0–20 cm partial core method that underestimated total C by ~35 % (Table 4). This method worked particularly poorly in *Sphagnum* bogs. The other partial coring methods worked better; the 50–100 cm partial coring predicted an average of 94 % of total C and had the lowest variability of all the methods tested (Table 4). The 25–75 cm partial coring methods did not work as well on this dataset as it did for the MN/MI cores, averaging only 85 % relative accuracy across the vegetation types although it did well for most of the peat vegetation types; C stocks in the *Sphagnum* type were underestimated by ~20 % (Table 4).

The intermittent core method had high predictive ability but also had the highest variability of all the methods tested

Table 2 Average (SE) peat and carbon properties, and water chemistry grouped by broad peatland vegetation types of cored peatlands in Minnesota and Michigan

Vegetation type					
	Sedge (*n*=8)	*Sphagnum* (*n*=10)	Ash (*n*=4)	Cedar (*n*=14)	Average
Thickness (cm)	80.6(6.3)	140.1(29.6)	57.5(12.7)	104.6(19.8)	95.7
pH	4.67(0.28)	3.87(0.08)	5.78(0.1)	6.40(0.10)	5.89
Conductivity (uS)	43.3(6.5)	52.0(2.7)	39.1(3.3)	179.0(29)	78.4
%C	42.9(1.11)	45.7(0.3)	38.7(1.24)	40.9(0.55)	42.1
BD (g cm^{-3})	0.12(0.02)	0.09(0.01)	0.16(0.01)	0.19(0.01)	0.14
Total C (MgC ha^{-1})	379(50.6)	664.6(188.5)	328(60.0)	807(121.9)	544.7
C density (gC cm^{-3})	5.51(0.7)	4.33(0.61)	5.79(0.32)	6.65(0.24)	5.57

(Table 4). Predicting total C using only peat thickness also had high relative accuracy. Peat thickness multiplied by the average C density (5.57 gC cm^{-3}, Table 2) averaged 107 % of total peat C stock, but this method also had high variability. The thickness only method worked well for all the vegetation types except for *Sphagnum*, which was overestimated by 20 %. Using a vegetation specific carbon density also had high predictive capacity, averaging 96 % relative accuracy with a low level of variability.

Discussion

More regions of the globe are being sampled for peat C stocks, and new methods are required to permit sampling and estimation in an efficient and cost effective manner (Warren et al. 2012). Sampling the entire peat profile is the most accurate method because the entire peat core is collected and processed to quantify total peat carbon stocks (De Vleeschouwer et al. 2010), but this process is time consuming, logistically challenging, and expensive, especially in landscapes with thick accumulations of peat. For instance, we subsampled from every 5 cm along the length of the core. In areas where peats are 5–10 m deep, this method requires 100–200 individual samples per core, all which need to be analyzed for bulk density and %C in the lab. To minimize sampling costs and effort, many studies subdivide whole cores into thicker subsections (e.g., every 50 cm: Chimner and Karberg 2008). This method provides empirical data on C content while reducing laboratory costs (e.g., a 5–10 m core would only need 10–20 individual samples per core). This method still requires the sampling of the entire peat profile, a problem in deep peats and/or remote areas.

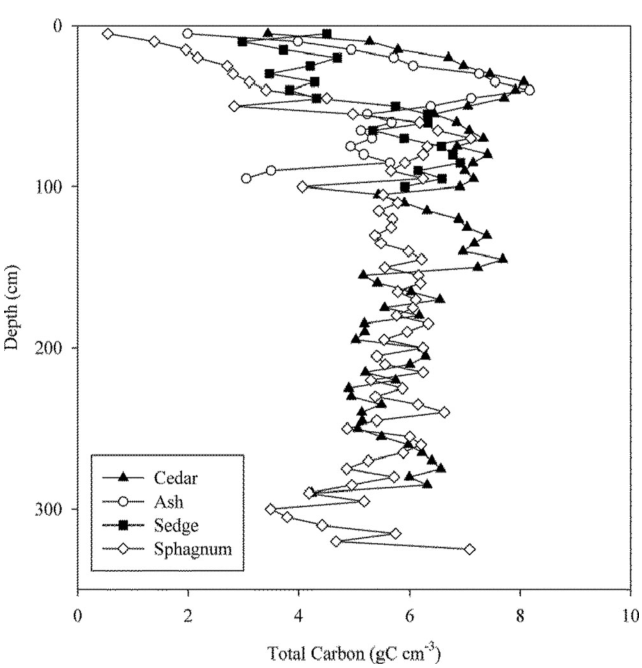

Fig. 1 Average total peat carbon by vegetation types at 5 cm depth increments. *Error bars* omitted for ease of viewing

To address these logistical issues, the intermittent method was developed to core deep Indonesian peats (Kauffman et al. 2011a). This method still requires coring the whole peat profile, but it only analyzes 5 cm subsamples from a few critical depths. Using this method, a 5–10 m core would only require 6–8 samples. Our test of this method showed good results with both the MI/MN and Manitoba data. The main drawback that we observed with this method is the high variability caused by natural soil C density variation with depth, particularly when applying 5 cm subsamples to larger depth sections. For example, if a 5 cm subsample was collected from a relatively low carbon density horizon, one would underestimate the carbon for a larger depth section. Another drawback of the intermittent methods is that the entire peat profile still needs to be cored, even though measurements and analysis only occur on the 5 cm subsamples. Logistically, sampling entire profiles can become difficult, especially for deep peat soils in remote areas.

The simplest method we tested was only sampling the thickness of the peat, which requires only measuring the thickness of the peat and multiplying it by an appropriate carbon density value. The easiest and most common way of

Table 3 Average (95 % CI) relative accuracy of rapid peat coring methods in Michigan and Minnesota separated by broad peatland vegetation types. Relative accuracy is the accuracy compared to whole core sampling (method total carbon estimate – whole core total carbon/whole core total carbon * 100)

Vegetation type	Sedge (*n*=8)	*Sphagnum* (*n*=11)	Ash (*n*=4)	Cedar (*n*=13)	Average (*n*=36)
Probe only	116(53.4)	152(36.9)	97(10.4)	85(5.9)	114(16.3)
Probe*vegetation	115(49.2)	118(32.3)	101(1.69)	102(8.2)	110(12.7)
Partial coring					
0–20 cm	68(43.0)	44(15.4)	72(12.5)	83(5.3)	67(9.4)
25–75 cm	97(6.2)	99(18.4)	126(11.8)	108(5.9)	105(6.7)
50–100 cm	134(38.5)	113(20.6)	92	103(6.1)	115(10.0)
Intermittent core	90(13.0)	90(12.9)	106(8.4)	94(8.4)	95(5.5)

doing this is to insert a probe into the peat soil until it hits the underlying mineral soil. The thickness only method is very fast and does not require the collection of samples or lab analysis. We found during our tests that the thickness only method was usually 85–90 % accurate compared to collecting the whole peat profile. Other studies have shown that actual peat thickness is well represented by probing when compared to ground penetrating radar (Parsekian et al. 2012). By stratifying peatlands into broad vegetation types, the accuracy may be increased to greater than 90 %. This thickness by vegetation method holds great promise for a rapid estimates of peat soil C stocks on a large scale, especially when collecting peat cores and analyzing them in a lab is not possible. However, errors can occur with this method by incorrect measurements of peat thickness. It can be sometimes difficult to detect the boundary between the bottom of the peat layer and the underlying mineral soil using a peat probe, especially if there are mineral layers in the peat (e.g., Chimner and Karberg 2008). It is easier to sample thickness in peatlands that are directly over sandy or loamy material; the sand "crunches" and refuses the probe. Clays and gytta can have a similar consistency as peat soils and are more difficult to detect; in these cases, it is easy to probe well past the peat/mineral interface and overestimate peat thickness. Thickness only measurements include one other source of uncertainty: representative values of average peat carbon density. Peat carbon densities change when peatlands are hydrologically altered (Schimelpfenig et al. 2014). Accurate estimates of regional average carbon densities would need to be developed with an extensive program of sampling whole profiles or possibly through a meta-analysis of the literature for the thickness only or thickness*vegetation method to be applicable.

Partial coring methods offer one alternative for assessing peat carbon densities that vary by peatland types and region. Partial core sampling requires more work and equipment than thickness only sampling, but is much easier and less costly than whole core or intermittent sampling. The premise of the partial core method is to sample peatland C at a depth that represents the average carbon density of the entire core. Thereby one can collect a single depth specific sample and apply that carbon density to the entire thickness. For the three partial core methods (0–20, 25–75, and 50–100 cm) tested here, we found that the 0–20 cm depth increment was the most unreliable, underestimating peat soil C stocks by >33 %. This

Table 4 Results of independent test of relative accuracy of rapid peat coring methods by broad peatland vegetation types using data from Zoltai et al. (2000). Average (95 % CI) relative accuracy is the accuracy compared to whole core sampling (method total carbon estimate – whole core total carbon/whole core total carbon * 100). Vegetation type refers to: 1=bog, 2=open fen, 3=shrubby fen, 4=treed fen, 5=hardwood swamp, 6=conifer swamp

Vegetation type	1 (*n*=32)	2 (*n*=12)	3 (*n*=3)	4 (*n*=3)	5 (*n*=2)	6 (*n*=11)	Average (*n*=63)
Probe only	120(7.3)	102(7.8)	98(14.7)	99(18.0)	90	93(7.1)	107(5.1)
Probe*vegetation	93(5.9)	101(7.5)	97(13.5)	98(15.9)	87	97(7.1)	96(3.7)
Partial coring							
0–20 cm	55(6.3)	87(12.0)	94(12.6)	49(24.9)	92	79(10.0)	64(5.9)
25–75 cm	79(5.5)	91(5.7)	93(1.2)	88(19.2)	103	90(7.6)	85(3.7)
50–100 cm	87(5.5)	93(6.9)	99(2.3)	99(11.3)	104	102(5.9)	94(3.5)
Intermittent core	114(6.7)	107(4.51)	105(2.4)	100(29.4)	52	81(32.5)	100(8.6)

*C-density used for vegetation types are as follows (general thickness only = 5.57, 1=4.33, 2=5.51, 3=5.51, 4=5.51, 5=5.79, and 6=5.79) result is not surprising as surface peat from many continental peatlands typically have the lowest carbon densities (e.g., Fig. 1), so if that layer is used to calculate the average core C density, it will always underestimate. We therefore recommend that this method not be used. Both the 25–75 and the 50–100 cm depth increments more closely represented the average C density. The 25–75 cm depth increment performed better than the 50–100 cm in MI/MN, but the 50–100 cm depth increment performed better in Manitoba.

Conclusions

This research was initiated to provide simple yet robust peatland C soil sampling protocols for the FIA program. However, these methods could apply to all peat sampling programs, but they should be properly tested before widespread use. We found that all the methods tested, except one the 0–20 cm partial coring method, are acceptable options for rapidly sampling peat C stocks. The simplest and cheapest methods involve sampling only the thickness of the peat and converting to C stocks by multiplying by a general or vegetation specific C density. We also found that with a small amount of field and lab work, one can collect a representative sample of peat (either partial or intermittent coring) and calculate C density for each core. For the FIA inventory program, based on our results, we recommend measuring peatland depth and vegetative cover (vegetative cover is already part of the FIA inventory) and sampling the 25–75 cm depth increment.

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