Uncertainty in Peat Volume and Soil Carbon Estimated Using Ground-Penetrating Radar and Probing

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Estimating soil C stock in a peatland is highly dependent on accurate measurement of the peat volume. In this study, we evaluated the uncertainty in calculations of peat volume using high-resolution data to resolve the three-dimensional structure of a peat basin based on both direct (push probes) and indirect geophysical (ground-penetrating radar) measurements. We compared volumetric estimates from both approaches, accounting for potential sources of error, with values from the literature. Approximate uncertainty of 14 to 23% was observed in the basin volume, and the total uncertainty roughly doubled when incorporating peat properties to derive the estimated C pool. Uncertainties in final C stock values are based on the uncertainty of the basin volumes and the variability in the peat properties and range between 31 and 38%. The results indicate that the well-established ground-penetrating radar technique that is scalable to larger peatlands can be used to obtain estimates of peat basin volumes at uncertainty levels similar to those for invasive direct probe surveys. This investigation demonstrated that ground-penetrating radar can quantify peat basin volumes at uniquely high spatial resolution without the need for extensive and invasive direct probing.

Abbreviations: CMP, common midpoint; GPR, ground-penetrating radar.

Peatlands store a large fraction of the global C in soil (Smith et al., 2004). Improving volumetric estimates of peat basins is a critical step to quantify the role of peatlands as a terrestrial C pool (Limpens et al., 2008). The amount of C contained in peatlands is uncertain because calculations of C stocks are often based on global estimates of average peat thickness (e.g., Gorham, 1991), estimated peat accumulation rates (Turunen et al., 2002), or sparse field data (e.g., Jaenicke et al., 2008). Peat thickness may be highly variable (Vitt et al., 2000); therefore, utilizing regional or global average depths for site-specific peat volume estimates could yield unreliable results. Many studies have shown that the ground-penetrating radar (GPR) geophysical technique has potential for the noninvasive determination of peat thickness on the basin scale (e.g., Lowry et al., 2009; Warner et al., 1990). The uncertainty in GPR-based volumetric estimates and significance with respect to estimating C stocks, however, has hitherto not been analyzed through direct comparison between basin volumes calculated from direct probe and geophysical peat thickness measurements.

Several studies have examined the potential of the GPR method to estimate peat thickness, noting the high correlation between probe and GPR depth estimates (e.g., Rosa et al., 2009). Rosa et al. (2009) also suggested that GPR may be effective at improving estimates of peat basin volume, although an investigation of the accuracy of such an estimate in relation to traditional probe measurements is absent from the literature. Studies investigating uncertainty in remotely sensed volume calculations have been completed for marine echo-sounding bathymetry

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methods in the ocean (Johnston, 2003). The different techniques used, physical properties, and unique subsurface features encountered in peatlands warrant a similar analysis of geophysical estimates of peat basin volumes. In this study, we utilized a database that combined GPR measurements and direct probe measurements collected at high spatial resolution relative to other peatland studies. Our goal was to demonstrate the variability inherent with each measurement approach as a step toward improving estimates of peatland basin volume that may be ultimately useful for refining estimates of C stocks in peatlands. This geophysical approach has the potential to improve peat volume measurements and thus C stock estimates, similar to how echo sounders revolutionized mapping of ocean basin volumes. We also considered the possibility of acquiring additional data on soil properties (e.g., C content) and the physical properties of peat (e.g., dielectric permittivity) simultaneously while acquiring basin volume estimates with GPR. Our results may be instructive for those designing surveys of peatland volume using either GPR, probe, or combined approaches.

MATERIALS AND METHODS

To compare the results of manual probe measurements with GPR determinations of peat basin volume, we used data collected as part of a climate change investigation on a boreal peatland (http://mnspruce.ornl.gov/content/spruce-project-documents). The study site is the S1 bog located approximately 30 km north of Grand Rapids, MN, in the Marcell Experimental Forest. The S1 bog has seen various forestry activities during the second half of the 20th century and is currently largely covered in dense vegetation composed of spruce trees <10 cm in diameter. Based on cores and trenching completed after this study, the mineral substrate below the peatlands in this area is a variable glacial till ranging from clay- to sand-textured sediments. This peatland is an ideal site to compare these measurement approaches because the peat thickness exhibits substantial variability and the 9.5-ha peatland is small enough to collect a dense grid of probe measurements across the entire surface. While we recognize that this study site is not representative of all types of peatlands, a particularly extensive data set is needed for such analyses and we took advantage of existing probe data that were collected at an unusually high spatial density that is unreported elsewhere for a peatland of this size.

During the summer of 2009, a total of 440 probe measurements (0.46 per 100 m^2, 53 person-hours distributed among four survey crews) were made using 0.5-cm-diameter metal rods at 176 predetermined locations laid out in a 20-m grid. Measurements were made by pushing the probe to the point of a contrast (rather than refusal), as determined by the operator feeling resistance. If a point of refusal was encountered in the very near surface, it would probably have been considered a buried log or root and the measurement was redone. Probe measurements were repeated three or more times at 85% of the plot centers, while one or two depth measurements were made at the remaining 15% of locations. The geometry of the probe locations at each plot was varied to make the measurements in hollows ensuring that the datum (i.e., approximately the water table) was as uniform as possible throughout the bog. Given the hummock–hollow topography, the measurements were sometimes clustered, while other times probe locations were somewhat uniformly distributed around the plot center within 1.5 m of the center point. At maximum, the distance between probe locations varied up to 2 to 3 m linear distance among points in a plot. The standard deviation of each cluster of $n \geq 3$ probe measurements was calculated and the mean standard deviation was used to evaluate the uncertainties in this approach.

A bootstrap Monte Carlo simulation was used to generate 5000 realizations of average peat volume, each based on 40 randomly selected probe locations (0.04 per 100 m^2) to illustrate the difference in resolution as a function of sampling density. The size of the subset was based on the approximate number of probe measurements that might be more representative of a typical investigation to characterize the morphology of a peat basin (e.g., n = 44 for an 8.7-ha basin, 0.05 per 100 m^2 [Buffam et al., 2010]). Although a regular grid would normally be used in the field for probe surveys (e.g., Buffam et al., 2010), the purpose of this simulation exercise was primarily to characterize the uncertainty related to using fewer sample locations. The random subsampling approach used in the Monte Carlo simulation is appropriate because it yields the maximum level of uncertainty due to the potential spatial clustering in the subsampled groups. The possible clustering may yield very large or very small volume results within the bootstrapping that would be avoided if a regular grid spacing was used. The mean was calculated for each of the 176 probe clusters, and 40 locations were randomly selected from the total number of clusters. The basin volume was calculated and stored for each iteration, and the mean and standard deviation of the all simulations were calculated. A Kolmogorov–Smirnov goodness-of-fit hypothesis test determined that the Monte Carlo results were normally distributed.

The GPR measurements were made during the winter of 2010 using a Malå 50-MHz rough-terrain antenna and Trimble global positioning system receiver to record positioning. Winter conditions allowed efficient travel across the bog surface, and the snow enabled the antenna to slide over the ground with relative ease. The instrument was set to make a measurement at 1-s intervals as the operator traversed the peatland with the antenna in tow, and >6450 time-triggered measurements (6.78 per 100 m^2) were collected. Initially, a grid sampling pattern was planned; however, on attempting to walk straight transects across the bog, it quickly became clear that the presence of many small trees would not allow regularly spaced continuous lines. Therefore, we chose a tortuous travel path of the instrument across the surface of the bog due to dense vegetation while making every effort to obtain even data coverage. Establishment of an explicit surface datum (i.e., in the way hollows were selected to make the probe measurements close to the water table) was not required for GPR because the radar velocity of the snow and dry peat material above the water table is nearly an order of magnitude higher than the peat so that the small unsaturated zone thickness is not discernible in the travel time measurement. The vertical resolution of this instrument is 0.18 m based on the commonly used quarter-wavelength calculation, implying that the antenna would theoretically not be able to resolve layers that are <0.18 m thick. Several additional profiling transects and three common-midpoint (CMP) GPR data sets were obtained in the summer of 2010 using 200-MHz antennas to determine site-specific electromagnetic wave velocities that allowed precise time-depth conversion of the GPR data (Greaves et al., 1996). Velocity determination required to convert measured two-way travel times to equivalent depth was performed using the hyperbolic basal reflection from each CMP radargram. Four linear profiles were also collected with 200-MHz antennas, although these data were not incorporated into the three-dimensional model because (i) the total spatial coverage was far less than the 50-MHz survey and (ii) the difference in resolution between these two frequencies would have made interpreting uncertainty overly complicated. The GPR survey required ~30 person-hours in the field including time for both depth sounding and CMP surveys. We evaluated uncertainties in GPR velocity estimates using the regression statistics method described by Jacob and Hermance (2004). Uncertainty in the depth determination was evaluated by calculating the repeatability of traces collected while the antennas were stationary using the standard deviation of the two-way travel times, incorporating sitewide velocity variability and adding the effect of the calculated vertical resolution for the 50-MHz antennas.

A model of the basin was created to calculate the volume from each data set. First, the depth data gathered with each method were merged with a polygon tracing the maximum extent of peat soil. Then, a three-dimensional grid with 1-m square (at depth = 0) cells was developed for each data set using triangle-based linear interpolation, and uncertainty associated with the interpolation was calculated in relation to the sampling density and interpolation method following Johnston (2003). Finally, the interpolated convex hull was integrated to resolve the volume. All depth uncertainty values were applied to volume estimates by using error propagation techniques and aggregated with the interpolation uncertainty. For the regional and global estimates of peat thickness, the volume was calculated simply by multiplying the estimated thickness by the surface area of the bog. Excluding the thin layer of living and undecomposed organic material above the water table, bulk density at the site ranged from 0.137 to 0.261 g cm^{-3} (Boelter, 1968; measured by drying and weighing a sample at field water content) or 0.176 $\pm$ 0.049 g cm^{-3}. Recent C content measurements from the peatland ranged between 0.45 to 0.51 kg C kg^{-1} dry peat (C. Garten, Oak Ridge National Laboratory, personal communication, 2010); in general, peat C content values are typically expected to vary by less than $\pm$5% (Vitt et al., 2000). These values result in an estimated C density of 0.084 $\pm$ 0.024 g C cm^{-3} that was used to estimate C stock from basin volume estimates.

RESULTS

Figure 1a shows an example of 200-MHz GPR data from the north-central section of the study site where the high horizontal resolution of the GPR data was corroborated by nearby probe measurements. The GPR velocity ranged between 0.0356 $\pm$ 0.0002 and 0.0377 $\pm$ 0.0005 m ns^{-1} with a mean of 0.036 m ns^{-1}. In the case of the CMP radargrams (example shown in Fig. 1b) used for velocity determination, this signal return from the basal reflector at about 100 ns was present from 0.4- to >5-m antenna separation. Therefore, >46 travel-time-offset pairs at 0.1-m trace increment were available for the velocity calculation and statistical analysis on each data set.

While the antennas were held stationary, the standard deviation was 0.37 ns (equivalent to <0.01 m) for 90 samples of mean travel times. The uncertainty associated with the interpolation of the GPR measurements was 0.09% of the estimated total volume. The maximum peat depth measured in the GPR survey was 8.6 m. Figure 2 shows the three-dimensional topography of the peat–mineral sediment contact as resolved using GPR (Fig. 1a), 176 equally spaced coincident probe measurement cluster locations (Fig. 1b), and a subset of 40 probe locations (Fig. 1c). The key features of the basin are a zone of >8-m peat thickness in

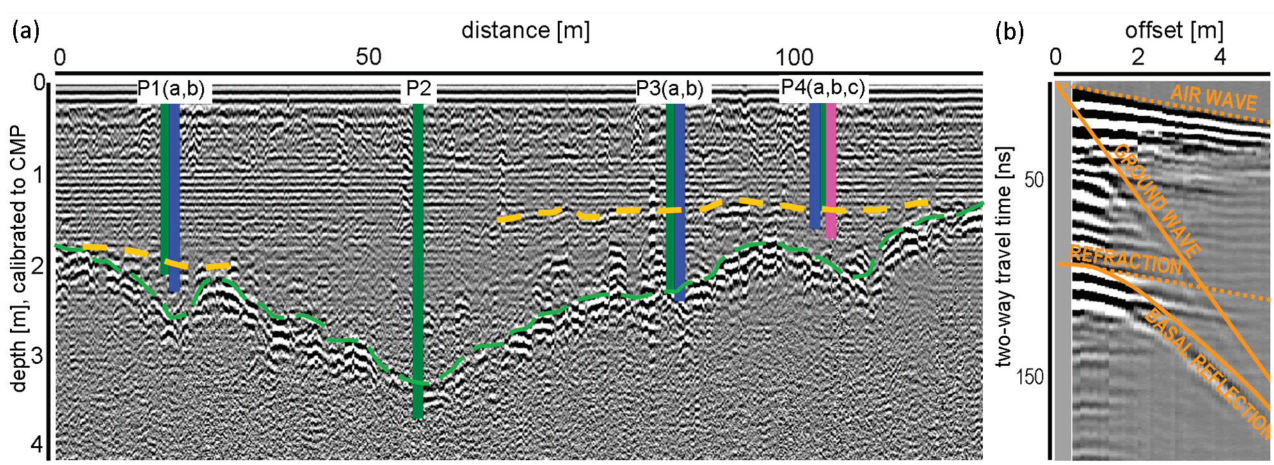

Fig. 1. (a) A radar profile that crosses the bog approximately horizontally at about 400 m, overlaid with probe data, with basal mineral soil reflection (green) and a laterally continuous horizontal stratigraphic layer (yellow) highlighted; and (b) a common-midpoint (CMP) radargram highlighting signal returns. Hyperbolic basal reflection used for velocity determination.

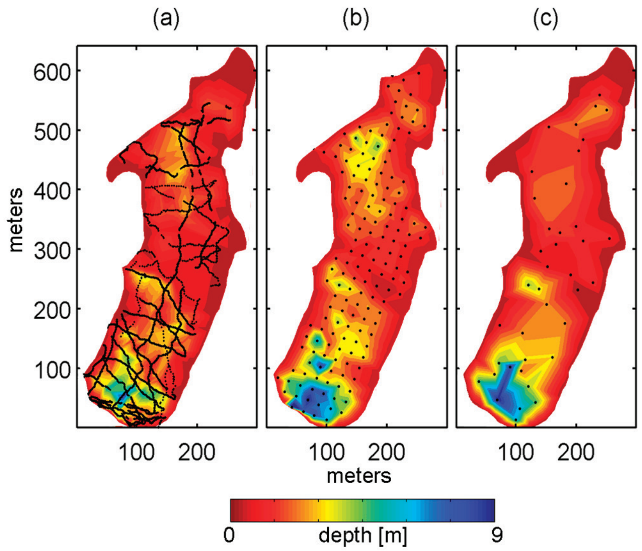

Fig. 2. Three-dimensional basin structure model calculated based on (a) ground-penetrating radar (GPR), (b) an evenly spaced grid of 176 probe clusters, and (c) a subsample of 40 probe clusters. Dark points indicate GPR trace locations or probe clusters located by global positioning system.

the southern end, a flat portion of ~0.5-m peat thickness in the middle, an area with >2-m-thick peat in the north, and shallow 0.5-m-thick peat at the very north end.

The mean standard deviation of probe measurements within a cluster was 0.22 m, while the mean difference between the maximum and minimum depth recorded within one cluster was 0.42 m. The maximum difference between measurements taken in the same cluster was 2.3 m in an area with an estimated peat thickness between 1.4 and 3.7 m. The maximum depth observed during the probe survey by a single measurement was 11.2 m. The uncertainty associated with the interpolation of the full set of probe measurements was 2.2% of the total estimated volume, while the interpolation uncertainty of the 40-location subset of probe measurements was 8.5%.

The peat basin volume determined using GPR and the measured CMP velocity at the field site was $1.33 \pm 0.31 \times 10^5$ m^3 (Table 1). If CMP data are not available, variability that could be encountered using maximum and minimum velocity values from the literature (Table 2) is from 1.22×10^5 to 1.81×10^5 m^3. The basin volume determined from the full set of 440 probe measurements in 176 clusters was $1.82 \times 10^5 \pm 0.26 \times 10^5$ m^3. The basin volume determined from the subset of 40 probe measurements was $1.60 \times 10^5 \pm 0.38 \times 10^5$ m^3. The results of the bootstrap Monte Carlo simulation were normally distributed at the $\alpha = 0.05$ level. Uncertainty in basin volume ranges from 14 to 23% of the estimated values.

Table 2. Electromagnetic wave velocity values for peat soils.

Source	Location	Velocity
		m ns^{-1}
Theimer et al. (1994)	various	0.035– 0.041
Jol and Smith (1995)	Alberta, Canada	0.04†
Slater and Reeve (2002)	Maine	0.0385†
Comas et al. (2005)	Maine	0.0345–0.0365
Emili et al. (2006)	British Columbia, Canada	0.038†
Lowry et al. (2009)	Wisconsin	0.035–0.047
Sass et al. (2010)	Tyrol, Austria	0.033–0.036
Parsekian et al. (2010)	Minnesota	0.036–0.049‡
Strack and Mierau (2010)	Alberta, Canada	0.033–0.044‡
This study	Minnesota	0.0356–0.0377
Range		0.033–0.049

† No range provided.
‡ Interval velocities.

We used the surface area of the S1 bog to calculate a peat volume based on an estimated average peat thickness for Itasca County, Minnesota (Soper, 1919), and from the global average estimated peat thickness (Gorham, 1991) as shown in Table 1. This comparison illustrates the peat volume that could be expected to result from using non-site-specific values. The conversion to C pools (i.e., measured basin volumes converted to C pool size based on peat properties) is also included in Table 1. Uncertainty in the C stock value is based on the uncertainty in the basin volume for each estimation approach and the variability in peat properties. These values range between 31 and 38%. Uncertainty could not be calculated for the volume or C content values derived from Soper (1919) and Gorham (1991) because uncertainty estimates for average peat thickness were lacking in those studies.

DISCUSSION

Subsurface Features and Ground-Penetrating Radar Velocity

An irregular subsurface morphology toward the southern end of the bog was revealed by high-resolution spatial data from GPR sensing, similar to studies on other peatlands (e.g., Rosa et al., 2009). The same basin structure interpolated from GPR data could also be used to calculate the slope of the basal reflector virtually anywhere within the peatland with a high level of confidence given the density of data points (e.g., Fig. 1a). A

Table 1. Peat basin volume estimates and associated uncertainty. Volumes reported for this study are based on interpolated three-dimensional basin structure; volumes associated with the studies of Soper (1919) and Gorham (1991) are simple multiplication of area and average thickness. Carbon stock calculations are for comparison purposes only and do not have uncertainty values.

Method	Avg. vertical uncertainty	Spatial uncertainty	Measurements per 100 m^2	Avg. depth	Volume	C stock
	m	%		m	$\times 10^5$ m^3	g C $\times 10^{10}$
Ground-penetrating radar	0.088	0.09	6.78	2.38	1.33 ± 0.31	1.12 ± 0.40
176 probes	0.228	2.20	0.46	2.60	1.82 ± 0.26	1.54 ± 0.48
40 probes	0.228	8.50	0.04	2.59	1.60 ± 0.38	1.28 ± 0.48
Soper (1919)	–	–	–	1.83	1.74	1.47
Gorham (1991)	–	–	–	2.3	2.19	1.85

qualitative evaluation of the basin models (Fig. 2) suggests that both probe measurements and GPR measurements resolved the same fundamental structural elements of the basin. The subset of 40 probe measurements resolved similar basin morphology to the full probe data sets, although the volumetric estimate was different. It is worth comparing the use of a regular grid sampling strategy for the probes with the quasi-random sampling strategy used for the GPR lines. Because the quasi-random resampling of the probe data resolved essentially the same subsurface features as both the full set of gridded probe data and the GPR data, it stands to reason that in this case the structure of the sampling strategy did not significantly affect the result. The basin model results are similar to three-dimensional models of other peatlands presented in studies using similar or lower probe sampling densities (e.g., Buffam et al., 2010; Lowry et al., 2009). The enhanced value of GPR data becomes apparent when considering the possibility of extracting information about the physical composition of the peat, as described below.

Our GPR depth estimates used to calculate basin volume have a variance in travel time of <0.33 ns for repeated traces. This is similar to the level of repeatability observed by Jacob and Hermance (2005), who noted a 95% confidence interval of 0.7 ns for two-way travel times in a sandy soil medium that had a higher radar wave velocity and therefore lower expected vertical resolution than peat. The observed variance translates into a repeatability of better than ± 0.01-m peat thickness and will not greatly impact volume calculations. Determination of the site-specific subsurface velocity is essential for accurate time–depth conversion of the raw GPR data (Greaves et al., 1996). Peat can support electromagnetic wave velocities between 0.033 m ns^{-1} (the approximate velocity of electromagnetic energy in water) in very high-porosity peat and 0.047 m ns^{-1} for lower porosity peat, although the most commonly reported velocities are between 0.033 and 0.040 m ns^{-1} (Table 2). In this investigation, we determined the site-specific velocity in an effort to minimize the uncertainty associated with GPR-derived volume estimates. Accurate velocity determination using multiple-offset GPR acquisition depends on resolving the hyperbolic reflection from the mineral soil at both small and large antenna offsets (Greaves et al., 1996). Our >46 travel-time-offset pairs per radargram allowed accurate velocity determination and error analysis, similar to previous analyses of CMPs (Jacob and Hermance, 2004). Additionally, the CMP method assumes a horizontally layered subsurface—an assumption that is well met in peatlands where the stratigraphy is nearly parallel and the slope of the basal reflector is low in most cases. Velocity uncertainty throughout the study site accounted for ± 0.078 m of error in GPR thickness estimates.

Errors and Uncertainties

Overall, the uncertainty between probe-based methods and GPR was similar: 15 to 24% of the total volume estimate. A source of error that is common to both GPR and probe-based calculations of peat volume is spatial interpolation. Our results are very similar to those of Johnston (2003), who use echo-sounding to determine that the interpolation uncertainty reduced to <1% of the total estimated basin volume with three or more measurements per 100 m^3. Similarly, Johnston (2003) observed a steep increase in uncertainty with fewer than one measurement per 100 m^3, in line with our probe surveys where the uncertainty rose to between 2.2 and 8.5% of the total estimated volume for the 176-point set and the 40-point set, respectively.

The volume estimate made using GPR was about 23% less than the estimate made using the full set of probe measurements. The subset of 40 probe measurements yielded a result that was about 17% larger than the GPR estimate. The larger volume estimate obtained with direct probes may be due to the possibility of pushing the probes slightly into the mineral substrate. This effect would be enhanced if there were spatial variability in the mineral substrate, such as lateral changes from coarse sediments (that compress very little) to softer clays. A variable substrate would result in probe depth uncertainties that would vary throughout the peatland, while the GPR response would be unaffected due to reflection simply arising from the change in water content between peat and inorganic sediments. Ground-penetrating radar relies on only a significant change in moisture content compared with the adjacent layer, and this will occur for any inorganic sediment (no matter what its compressibility) encountered at the base of a peatland. Also, nonvertical probe orientation or curvature of the rods may have exaggerated the depth measurements, especially in the deepest peat. We speculate that deep woody debris, small-scale lateral variability in the sediment composition, localized variability in the basal mineral sediment height, operator error, or some combination of these factors may be the cause in instances where large depth variability was observed within a single probe cluster.

An additional uncertainty factor is that the GPR footprint becomes wider with increasing distance from the antenna (Baker et al., 2007), meaning that the area of the basal sediment that is being averaged is larger for greater depths. In contrast, the tip of the probe always samples the same small area regardless of depth. These possible factors would be consistent with observations made by Rosa et al. (2009), who revealed larger discrepancies between probe and GPR measurements in thicker peat. We speculate that the large footprint at depth is a key reason that the GPR did not detect the deepest, isolated low points observed in the probe measurements.

Although a direct one-to-one comparison between GPR and probe depths was not possible for this study because the GPR lines did not directly cross point locations, we scaled the GPR results to the 20-m probe grid spacing to make a quasi-one-to-one comparison. Figure 3a shows the difference between the two measurement techniques spatially. As would be expected (e.g., Rosa et al., 2008), the largest discrepancies were encountered at the south end of the bog with the deepest peat, while the shallower peat had essentially random, low variability. The one-to-one comparison of the upscaled-GPR data with the probe data (Fig. 3b) reveals that most locations had a good correspondence, although the deeper measurements encountered larger variability. A slight bias toward

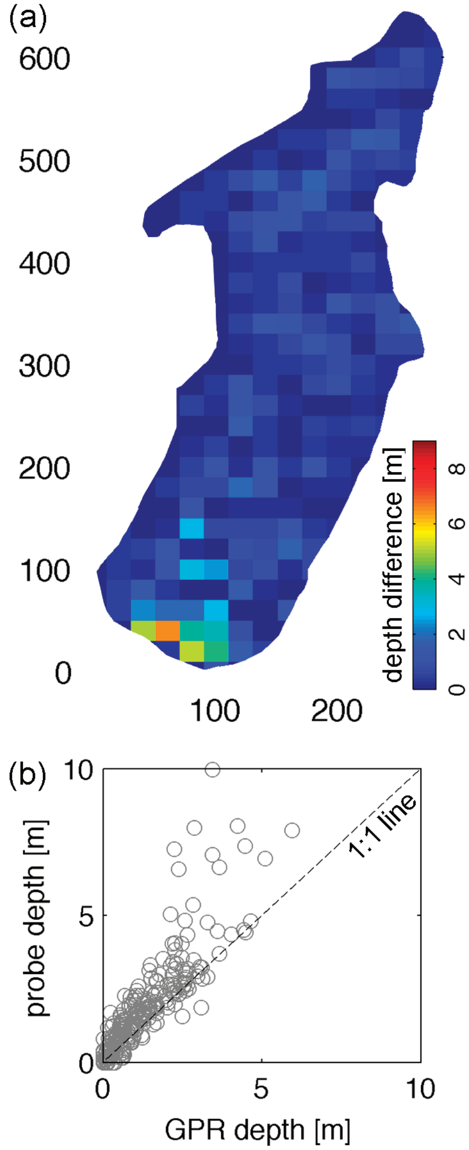

Fig. 3. (a) Comparison of upscaled ground-penetrating radar (GPR) data with probe data across the S1 bog showing areas of measurement discrepancies; and (b) a one-to-one comparison between GPR and probe data showing a good correspondence with a slight bias toward probe measurements, which indicates a potential slight underestimate of GPR velocity ($y = 1.3x$, $R^2 = 0.75$).

probe measurements can be seen in Fig. 3b, suggesting that the GPR velocity estimate was low. An erroneously low GPR velocity estimate could explain a systematic underestimate of peat thickness, yielding a smaller basin volume. Although we did make several multiple-offset GPR measurements in the bog to characterize the velocity, it is possible that spatial variability in the peat properties outside our multi-offset measurement sites would have justified the use of larger velocity values.

As would be expected (e.g., Johnston, 2003), the volumetric estimate made using the largest sampling density (GPR, $n = 6.78$ per 100 m^2) had smaller calculated uncertainty than those approaches that used fewer measurements (probe, $n_{total} = 0.46$ per 100 m^2 and $n_{subset} = 0.04$ per 100 m^2). The estimate made using the global estimated peat thickness (Gorham, 1991) yielded the largest basin volume, while the regional estimated average peat thickness (Soper, 1919) resulted in a volume between the GPR and probe estimates. Uncertainties could not be evaluated for the estimated average peat thicknesses, so these values are included primarily for illustrative comparison to conceptually simple approaches that are often used to regionalize peat inventories.

The GPR survey required the least amount of field time and generated the largest number of data points, although the instrumentation is much more expensive than the metal rod used for probe measurements and GPR requires a trained operator. Even though the probe method may encounter problems with misidentification of the basal sediment depth (Rosa et al., 2009), the potential to assess the uncertainty by making repeated measurements is valuable. Nonetheless, our results clearly indicate that an appropriate sampling density must be used to ensure that the uncertainty estimate in volumetric calculations is acceptably small or the peatland must be known to have a simplistic basin geometry that can be resolved with fewer probe locations (e.g., Buffam et al., 2010). Avoiding excessive probe measurements by using GPR may be desired if the peatland will be studied over time. It is possible that repeated breaching of the peat by the probes may alter small-scale hydrology and could disrupt the natural release of gas from the subsurface by creating preferential flow paths. In turn, this could impact the ecology of the surface vegetation, which is often sensitive to the state of the subsurface (e.g., Weltzin et al., 2000). Although the living portion of the acrotelm layer may grow to cover the holes relatively rapidly, the catotelm disturbance would probably remain indefinitely.

We observed 14 to 23% uncertainty in the basin volume, and the total uncertainty roughly doubled when peat properties were incorporated to derive the estimated C pool. This indicates that characterization of peat properties (primarily bulk density) is approximately equally as important as a reliable estimate of the basin volume when seeking to reduce uncertainty. Carbon density estimates at this peatland fell within a narrow range of 0.45 to 0.51 kg C kg^{-1} dry peat. Because these values are more predictable, generally expected to vary <5% (Vitt et al., 2000), it is probable that C density characterization is somewhat less important than the basin volume estimate or bulk density in the final C stock estimate.

Extracting Bulk Density Information from Ground-Penetrating Radar Data

A potential advantage to utilizing GPR measurements for peat volume estimates is that more information is contained within the GPR data than peat depth alone. It has been well documented that GPR velocity analysis (e.g., Fig. 1b) can reveal the subsurface dielectric permittivity structure– a physical property that is closely related to water content and free-phase gas content of peat soils (e.g., Comas et al., 2005). Determining bulk density across a wide spatial scale within a peatland could help to considerably reduce uncertainty in the total C pool. Warner et al. (1990) suggested that GPR may respond to bulk density variations—that is, a relationship might exist between peat bulk density and dielectric permittivity. The potential therefore exists to improve C stock estimates in peatlands if the relationship between dielectric permittivity and bulk density can be quantified and emerging spatially continuous multiple-offset GPR technologies (e.g., Gerhards et al., 2008) can be applied to characterize the subsurface physical properties of peatlands in a semi-continuous mode.

We therefore performed an extensive literature review of studies reporting both measured bulk density and dielectric permittivity of peat samples (i.e., as measured by GPR or time domain reflectometry). Although a number of researchers have reported both values, we could find no studies in the literature that specifically reported on a relationship between the relative dielectric permittivity and bulk density of peat, and therefore we attempted to develop this relationship ourselves. We collected a total of 23 measurements from nine studies (Fig. 4). Each data point represents a relative dielectric permittivity value (i.e., the physical parameter derived from a GPR measurement) for a "saturated" peat sample along with a bulk density measurement (determined by various methods). If a significant relationship between relative dielectric permittivity and bulk density were found within the data set, it would be plausible to assume that GPR could be used to estimate the bulk density of peat and infer the C content. Although the trend of the regression is what we might expect (i.e., relative dielectric permittivity increases as bulk density decreases), we found that the relationship was not statistically significant (P = 0.39) and had a low coefficient of determination (R^2 = 0.03). This indicates that the model only described about 3% of the variation in the data and suggests that GPR is relatively insensitive to bulk density in natural peat soil samples. We leave the opportunity open for further investigations—it is possible that a dedicated study may be able to reveal a more coherent relationship between these parameters (at least at the site level), and this relationship would be highly valuable to those attempting to estimate soil C stocks in peatlands. We speculate, however, that the presence of free-phase gas trapped within the peat (>10% in some cases, e.g., Comas et al., 2005) will make this a challenging relationship to elucidate.

CONCLUSIONS

Both GPR and probe measurements resulted in estimates of peat volume with approximately the same level of uncertainty. Ground-penetrating radar yielded a denser distribution of data points that may be useful for characterizing basin slope and provide estimates of physical properties (i.e., dielectric permittivity). With continued research into the relationship between bulk density and dielectric permittivity, this geophysical method could aid in determining useful soil properties of the peat. While manual probes will continue to be a valuable tool to study peat, we have shown that an established, noninvasive geophysical imaging tool also has the potential to estimate peat basin volumes—an essential factor when calculating C stock in peatlands. The GPR technique could improve peatland C stock estimates in a similar way to how the echo sounder improved volume estimates of the ocean basins. Broader use of GPR surveys to estimate peat basin volumes (e.g., sled or vehicle mounted) could considerably reduce uncertainty in global C stocks. As shown by both the push probe and GPR approaches, peatlands may have complex morphology that requires thorough characterization to yield reliable estimates of C content. When using GPR surveys, it is important to stress the value of site-specific velocity measurements to improve the volumetric estimate and uncertainty calculations and to potentially estimate properties of the peat.

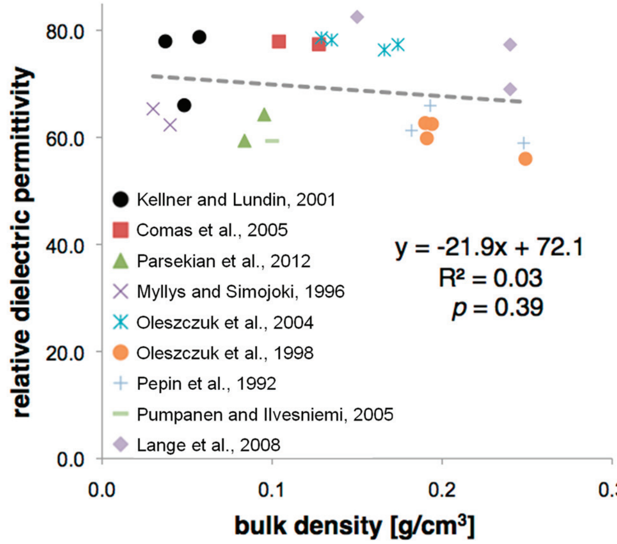

Fig. 4. Relationship between dielectric permittivity and bulk density of peat as determined from a literature review. Gray line is the regression fit to all of the data.

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