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Journal of Geophysical Research: Biogeosciences

RESEARCH ARTICLE
10.1002/2013JG002411

Key Points:
- Peat depths measured concurrently using GPR and manual probing disagree
- Error caused by probes being obstructed or extending into underlying sediments
- GPR surveys calibrated using CMP are most reliable for measuring depth

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Evaluating approaches for estimating peat depth

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Abstract Estimates of peat depth are required to inform understanding of peatland development, functioning, and ecosystem services such as carbon storage. However, there is a considerable lack of peat depth data at local, national, and global scales. Recent studies have attempted to address this knowledge deficit by using manual probing and ground-penetrating radar (GPR) to estimate depth. Despite increasing application, little consideration has been given to the accuracy of either of these techniques. This study examines the accuracy of probing and GPR for measuring peat depth. Corresponding GPR and probing surveys were carried out at a catchment scale in a blanket peatland. GPR depth estimations, calibrated using common midpoint (CMP) surveys, were found to be on average 35% greater than probe measurements. The source of disagreement was found to be predominantly caused by depth probes becoming obstructed by artifacts within the peat body, although occasionally probing rods also penetrated sediments underlying the peat. Using the Complex Refractive Index Model, it was found that applying a single velocity of 0.036 m ns^{-1} across a single site may also result in −8 to +17% error in estimation of peat depth due to spatial variability in water content and porosity. It is suggested that GPR calibrated at each site using CMP surveys may provide a more accurate method for measuring peat depth.

1. Introduction

Many of the ecosystem services provided by peatlands are delivered due to processes which occur beneath the surface and extend throughout the whole peat profile [*Parry et al.*, 2012]. Peat depth can be considerably variable both within and between individual peatlands, and information on peat depth and morphology is regularly required to inform our understanding of peatland development and functioning. For example, peatlands globally form a considerable carbon stock and have an important role to play in the global carbon cycle [*Yu*, 2012]. Peat depth data sets are an essential component of carbon accumulation calculations [*Gorham*, 1991; *Loisel et al.*, 2013; *van Bellen et al.*, 2011] and also in developing carbon inventories and maps of carbon distribution [*Beilman et al.*, 2008; *Sheng et al.*, 2004; *Parry and Charman*, 2013]. These data are subsequently used in global climate change models [*Charman et al.*, 2012] and to justify land management decisions [*Frogbrook et al.*, 2009]. As a result, accurate representation of peat depth is essential in informing our understanding of peatland development and functioning. Despite this, there is often considerable lack of peat depth data at local, national, and global scales [*Parry et al.*, 2012; *Yu*, 2012]. At present, two techniques are commonly applied to measure the depth of peat: (1) manual probing with metal rods, which records depth at intervals across a peatland, and (2) ground-penetrating radar (GPR), a geophysical technique which can semicontinuously image the base of peat.

Manual probing involves pushing an extendable metal pole (~ 1 cm in diameter) into the ground until the point of resistance and recording the depth and position with a global positioning system (GPS). This technique is cheap and technically very simple and consequently is favored by a number of studies. Probing has been used for many years to map peatland resources and carbon stocks in the United States and Canada [*Bjelm*, 1980; *Worsfold et al.*, 1986; *Buffam et al.*, 2010; *Beilman et al.*, 2008] and Europe [*Charman,* 1995; *Valpola et al.*, 2012; *Parry et al.*, 2012; *Holden and Connolly*, 2011]. Recently, probing has also been used in the exploration of tropical peatlands [*Householder et al.*, 2012]. Moreover, manual probing is commonly used by government agencies, land owners, and nongovernmental organizations to inform management, development, and environmental designations on peatlands. For example, in Scotland, probing is a recommended technique for informing the design layout during the construction of wind farms [*SEPA and Scottish Renewables*, 2012]. Despite the common application of manual probing, there has been little investigation into its accuracy and it is assumed that probes consistently meet the base of peat. However, *Sass et al.* [2010] carried out a number of manual probe measurements in terrestrialized

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mires in Austria and suggested some probes may either have become obstructed by artifacts within the peat or were extended into soft subpeat layers, such as clay. Peat profiles from different mire types can vary considerably in the vegetation they are composed of, the degree to which they are decomposed and the rate of transition to the peat mineral interface. For example, in the UK, many blanket peatlands formed by paludification and often have birch remains within the peat profile [*Tallis and Switser*, 1983], while peatlands in boreal regions formed by terrestrialisation may have soft lake sediments (gyttja) occurring beneath them. These features may cause peat probes to fail to meet the true peat-mineral interface or to intrude into it, thus introducing error in peat depth measurements.

GPR is a well-established geophysical technique which can be used to semicontinuously map the interface between a peat deposit and the mineral subsurface [*Bjelm*, 1980; *Worsfold et al.*, 1986; *Warner et al.,* 1990; *Rosa et al.,* 2009; *Holden et al.*, 2002]. GPR is a noninvasive technique and is capable of recording thousands of closely spaced data points, and consequently, GPR has been used in many studies requiring a detailed understanding of peatland morphology. For example, depth data sets derived by GPR have been used to imply processes of peat development [*Comas et al.*, 2004, 2005b; *Loisel et al.*, 2013] and quantify temporal change in peatland carbon accumulation [*van Bellen et al.*, 2011]. A GPR consists of transmitting antenna which emits an electromagnetic wave (EMW) into the ground surface and a receiving antenna which detects the reflections of the EMW. Reflections are caused when dielectric permittivity (ε_r), which is primarily determined by moisture content, changes abruptly within the peat profile [*Theimer et al.*, 1994]. The typically sharp contrast in moisture content at the peat to mineral interface means a strong and continuous reflection is recorded by the GPR, providing a profile of peat depth [*Bjelm,* 1980; *Warner et al.*, 1990; *Rosa et al.,* 2009]. The time period between the EMW being emitted from the transmitting antenna, reflected as a result of a change in ε_r, and detected by the receiving antennae is known as the two way travel time (TWTT) [*Neal*, 2004]. The TWTT of the peat mineral interface reflection can then be converted to peat depth with the EMW velocity. A simplified form of the EMW velocity can be defined as

$$v = \frac{C_0}{\sqrt{\varepsilon_r}}, \tag{1}$$

where v = velocity (m ns^{-1}) and C_0 is electromagnetic wave velocity in a vacuum (0.3 m ns^{-1}) [*Neal*, 2004]. Using an accurate EMW velocity is essential if peat depth is to be recorded correctly. The EMW velocity is primarily determined by ε_r of the peat (see equation (1)). Saturated peat typically has ε_r values of between 57 and 80 [*Neal*, 2004; *Theimer et al.*, 1994; *Slater and Reeve*, 2002], and geological materials do not have ε_r above that of fresh water (82 at 5°C). Moisture content, bulk density, and degree of humification determine ε_r and consequently EMW velocity within peat [*Comas et al.*, 2004; *Theimer et al.*, 1994; *Warner et al.*, 1990]. These physical properties have been shown spatially to be highly variable both between and within individual peatlands [*Baird et al.*, 2008; *Morris et al.*, 2011; *Lewis et al.*, 2012]. Some temporal variability in velocity has also been demonstrated by *Comas et al.* [2005a] in EMW velocity, as a result of a change in levels of free phase gas within the peat. Consequently, it is often suggested that multiple velocity calibrations are necessary to find an accurate average GPR velocity for an individual peatland [*Theimer et al.*, 1994; *Lowry et al.*, 2009; *Rosa et al.*, 2009; *Parsekian et al.*, 2012].

Two techniques can be used to calibrate EMW velocity: (1) manual peat depth probes, where velocities are derived empirically from a probe-measured depth and EMW TWTT [*Theimer et al.*, 1994], and (2) common midpoint (CMP) surveys, where the transmitting and receiving antennae are moved apart at set intervals and increases in TWTT are used to calculate velocity [*Neal*, 2004]. *Rosa et al.* [2009] identified statistically that at least 30 manual probe measurements are needed in order to accurately account for variability found in EMW velocity for each discrete area of peatland but do not critically analyze either technique. CMP surveys are favored by some studies, including *Strack and Mierau* [2010], *Jol and Smith* [1995], and *Kettridge et al.* [2008], as the peat to mineral interface can be identified with a greater amount of certainty. However, typically fewer CMPs are gathered per survey than manual probe calibrations (see Table 1).

Probing is a commonly applied technique for measuring peat depth, but little consideration has been given to the accuracy of these depth measurements. As manual probing is used for both independent measurements of peat depth and for the calibration of EMW velocities used in GPR depth measurements, evaluating the accuracy of this methodology is crucial. The aim of this study is (1) to identify the most appropriate methodologies for calibrating GPR surveys in peatlands, (2) to investigate the accuracy of manual

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Table 1. An Overview of Published EMW Velocities Calculated for Peat and the Methodology Used to Gather Them[a]

Reference	Mean Velocity (m ns^{-1})	ε_r	Number of Samples (n)	Type
Rosa et al. [2009] Site one	0.040	56	110	Probes
Rosa et al. [2009] Site two	0.039	59	65	Probes
Sass et al. [2010]	0.038	62	10	CMP
Strack and Mierau [2010]	0.036	69	6	CMP
Theimer et al. [1994]	0.037	66	13	Probes
Jol and Smith [1995]	0.040	56	1	CMP
Kettridge et al. [2008]	0.035	73	3	CMP
Comas et al. [2005a]	0.041	54	3	CMP
Comas et al. [2004]	0.038	62	—	CMP
Comas et al. [2005b]	0.035	73	—	CMP
Comas et al. [2005c]	0.035	73	—	CMP
Parsekian et al. [2012]	0.036	69	3	CMP
Kettridge et al. [2012]	0.036	69	—	CMP
Loisel et al. [2013]	0.037	66	—	Probes
van Bellen et al. [2011]	0.040	56	—	CMP and Probes
	0.046	43	—	
Mean value	0.038	63		
Standard deviation	0.003	8		

[a]A dash line indicates value not stated within the source reference.

probing to measure peat depths, and (3) to discuss the implications that inaccurate depth measurements may have upon the calibration of GPR surveys.

2. Study Site

Surveying for this study was carried out on a 25 ha area of Keasdon Moor, a blanket peatland in Lancashire, United Kingdom (54°02′N, 2°24′W and 340 to 400 m above mean annual sea level) in November 2011. The site is underlain by Millstone Grit, where poor drainage as a result of glacial till clay has resulted in the accumulation of blanket peat of up to seven meters in depth. This area is classified by the National Soil Research Institute as Winter Hill, a poorly humified and *Eriophorum* sp. rich peat [*Avery*, 1980]. The vegetation consists predominantly of cotton grass *Eriophorum* sp. and heather *Calluna vulgaris*, with isolated areas of *Sphagnum* sp. Surface conditions are variable, with active artificial drainage ditches and natural gullies in the north and intact blanket peatland in the south of the site.

3. Methodology

3.1. GPR Surveying

Eight kilometers of common offset GPR data were gathered using Mala 100 MHz and 250 MHz shielded antennae. Each antenna was mounted on a wooden sled and towed at walking pace behind a low ground pressure tracked vehicle. A real-time kinematic (RTK) differential GPS (dGPS) was connected to each GPR system and used to trigger and log the position of each GPR trace at 0.25 s intervals. These data were subsequently post processed to give centimeter level accuracy. The GPR unit was set to record at a 600 ns time window, with data stacking at 16 measurements. A gridded survey design was originally planned. However, due to the rough nature of the terrain, it was not always possible to keep to the specified tracks (Figure 1). Three independent common midpoint (CMP) surveys were also carried out using a Pulse Ekko Pro system with 500 MHz antennas, each in an area of differing moisture conditions. Two antennas were moved separately out from a midpoint at 0.04m intervals; this allowed the collection of data from a reflector at an increasing offset [*Jol and Smith*, 1995]. Velocity can then be obtained from the basal reflector hyperbola with a least squares routine [*Neal*, 2004].

GPR data were postprocessed and analyzed in REFLEX W version 6.0.5 (K. J. Sandmeier, Karlsruhe, Germany). The following processing steps were applied to the common offset survey data: a "dewow" filter to remove low frequency noise, a time-zero correction, and an automatic gain control (AGC) gain function, to ensure the peat to mineral interface was distinctly visible. The continuous picking function was used to manually select the peat mineral interface in REFLEX W. The peat to mineral interface reflector was picked at the point where

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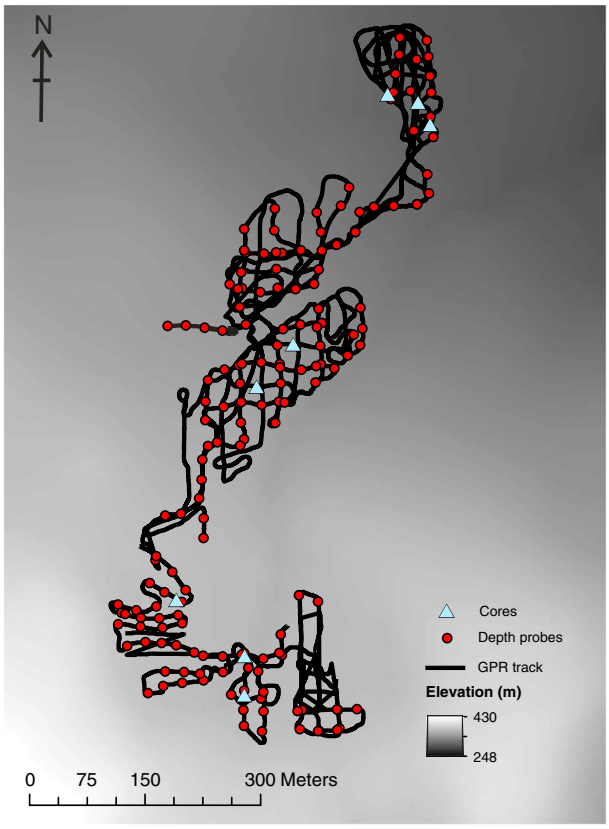

Figure 1. Site map outlining GPR tracks and depth probe and coring locations.

strong deviations in the waveform occurred. These points were only picked where they were supported by adjacent traces with similarly strong reflections at approximately the same TWTT (these types of reflection are evident in Figure 5). The TWTT and coordinates for these picks were then exported into *arc*GIS version 10 using the RTK dGPS coordinates in WGS 1984.

3.2. Manual Probing and Coring

While the GPR survey was being carried out, 162 points were marked on the ground using survey flags. The location of each flag and the corresponding label were recorded using the RTK dGPS. Following the GPR survey, peat depth was measured manually at each of these points. An extendable steel probe was pushed into the peat until the point of resistance and the depth recorded. In order to account for local depth variability, three replicate depths measurements were recorded at each point, within 0.5 m of each other. Eight full profile Russian cores of differing depth were sampled in line with the GPR tracks. Each Russian core extracted took considerable effort to sample and was struck with a large mallet in order for retrieval of the full peat depth. The position of each core was logged using a Trimble GEOXH dGPS, which has a postprocessed accuracy of <10 cm. Each core was analyzed at a 5 cm resolution for loss on ignition (LOI), bulk density, and Von Post classification [*Von Post*, 1924].

4. Results and Discussion

4.1. Comparison of Manual Probe and GPR Depths

Each CMP survey carried out returned a hyperbolic reflection at the peat to mineral interface (Figure 2). Velocities of 0.0348, 0.0360, and 0.0372 m ns^{-1} were returned. The mean velocity resulting from the CMPs (0.036 m ns^{-1}, $\varepsilon_r = 69.4$) was used to calculate the corresponding GPR depth at each of the 162 manually probed depth points. A strong positive correlation was found between the GPR and manually probed depths (Figure 3), with an r^2 value of 0.85 significant to $P < 0.05$. Despite this, the GPR and probed depths are not in 1:1 agreement (Figure 3). The manually probed values are on average 35% shallower than GPR derived depths. In 9% of the sampling points, the depth obtained from using a probe was over 1 m shallower than the depth derived from using the GPR (Figure 3).

Clearly, either the GPR or manual probing methodology is resulting in inaccurate depth measurements. The following sections of this paper aim to investigate the source of this error, which could result from three causes: (1) inconsistency in GPR radar picks, (2) natural variability in EMW velocity caused by varying dielectric permittivity, or (3) manual probes not consistently meeting the peat to mineral interface.

4.2. Consistency of GPR Radar Picks

In order to quantify the consistency of TWTT peat to mineral interface picks, 100 points at which the GPR tracks intersects itself (Figure 1) were identified and converted to depth using a velocity of 0.036 m ns^{-1}. Intersecting GPR traces had a mean difference in depth of 0.11 m with a standard deviation of 0.09 m. The vertical resolution of 100 MHz GPR survey in peat is close to this value at approximately 0.1 m [see *Slater and*

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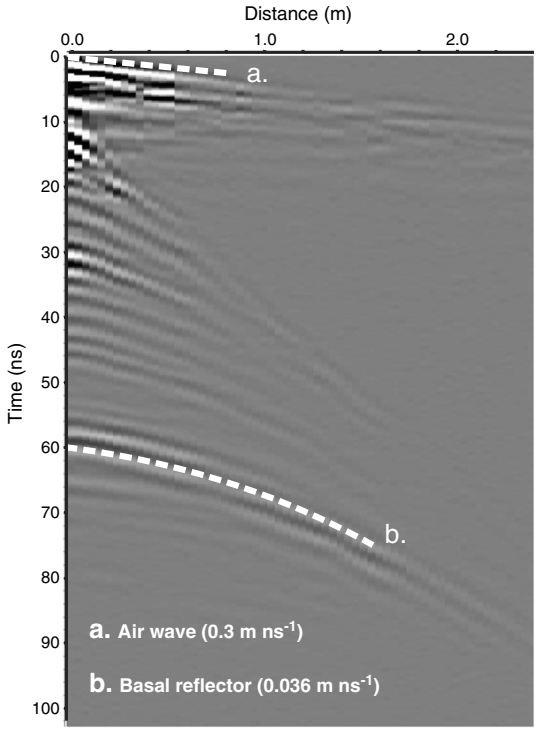

Figure 2. A CMP gather demonstrating NMO basal reflector used to calculate velocity.

Reeve, 2002; *Theimer et al.,* 1994]. Consequently, much of the difference observed at the intersecting GPR tracks is likely to be as a result of the GPR vertical resolution.

4.3. Natural Variability in Dielectric Permittivity

To calculate the error associated with using a single EMW velocity across a whole site, we applied a volumetric mixing model for soil known as the Complex Refractive Index Model (CRIM) (equation (2)) to estimate the ε_r for a matrix of typical porosity and water contents:

$$\varepsilon_{r(b)} = \left(\theta\varepsilon_{r,w}^{\alpha} + (1-n)\varepsilon_{r,s}^{\alpha} + (n-\theta)\varepsilon_{r,a}^{\alpha}\right)^{\frac{1}{\alpha}} \quad (2)$$

where θ = volumetric soil water content, n = porosity, $\varepsilon_{r,w}$ = dielectric permittivity of water (82 at 5°C from *Neal* [2004]), $\varepsilon_{r,s}$ = dielectric permittivity value of dry peat (2) [value from *Comas et al.*, 2005a], and $\varepsilon_{r,a}$ = dielectric permittivity value of air (1). A curve fitting factor (α) accounts for the geometric arrangement of minerals and the orientation of the electrical field [*West et al.*, 2003]. *Kellner and Lundin* [2001] have calibrated peat finding a curve fitting factor (α) of 0.35, which has commonly been used in subsequent studies such as *Parsekian et al.* [2010], *Comas et al.* [2005a] and *Strack and Mierau* [2010].

Peat has high water content and high porosity [*Hobbs*, 1986], typically with water contents of more than 80% [*Shotbolt et al.,* 1998; *Theimer et al.,* 1994], porosities of greater than 80% [e.g. *Comas and Slater,* 2007; *Lewis et al.*, 2012; *Theimer et al.*, 1994] and gas contents of less than 20% [*Rosenberry et al.*, 2006] and these values were used to form the CRIM matrix in this study. The resulting ε_r were then converted to velocity (m ns^{-1}) using equation (1) and the percent difference from 0.036 m ns^{-1} found (Figure 4). We found that the error introduced as a result of using a single velocity across an entire peatland may cause an underestimation in peat depth of −8% and an over estimation of 17%.

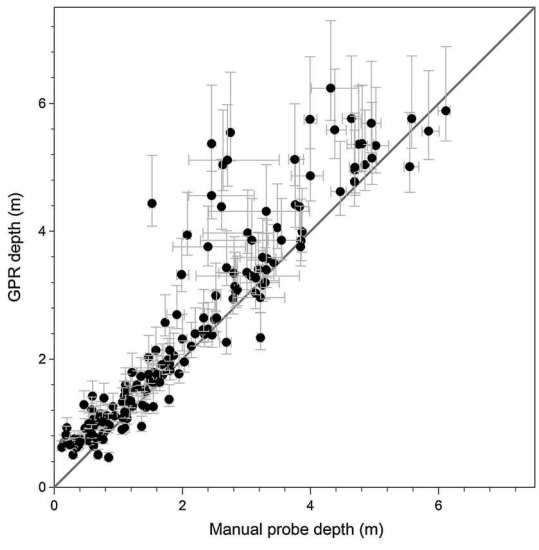

Figure 3. A comparison of manual probed depth and GPR depth using a velocity of 0.036 m ns^{-1}. Line represents 1:1 agreement. Manual probing error bars are maximum, and minimum probe depths and GPR depth error bars represent error caused by variability in GPR velocity.

4.4. Error in Measurement Techniques

At each sampling point, it was investigated whether there was any correspondence between the quantifiable error range of manual probe and GPR depth measurements. Error associated with spatial variability in velocity (see section 4.3) and resolution and picking consistency (sections 4.2) were used as the GPR error range. In addition, sampling points with manual probing depths of less than 0.8 m were discounted in order to remove uncertainty in picking as a result of ground wave interference. The range of replicates at each sampling point was used for manual probing error. At 25% of sampling points

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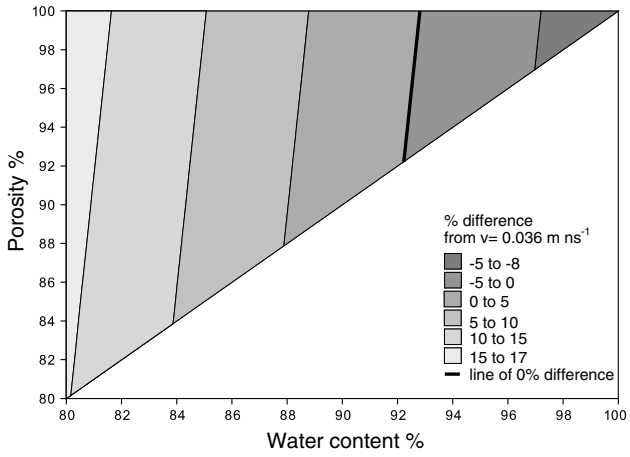

Figure 4. Contour plot demonstrating the error in velocity (%), and consequently depth, calculated when using a standard peat velocity of 0.036 m ns^{-1} under varying possible water content and porosities in peat. Dielectric permittivity was calculated using CRIM and converted to velocity using equation (1).

the manual probe and GPR depths did not correspond despite full consideration of quantifiable error. Consequently, a large proportion of the disagreement discussed in section 4.1 cannot be associated with known sources of GPR error or inconsistencies in manual probing.

4.5. Velocities Calculated Using Manual Probing

If the 162 probe measurements and their corresponding TWTT are used to calculate an EMW velocity, a mean value of 0.0301 m ns^{-1} is returned (standard deviation 0.0085 m ns^{-1}). This mean velocity is considerably slower than velocities recorded on the same site using CMP surveys (see section 4.1) and other peatland EMW velocities reported in the literature (see Table 1).

When velocity values calculated by probes are converted to ε_r using equation (1), a mean value of 99 is returned. Only 31% of ε_r recorded fall within the range typical for peats of 57–82 (see section 1). Furthermore, when only the 25% of sampling points where depth disagreement cannot be explained by error are considered (section 4.4), a ε_r of 114 is calculated. In addition, none of the calculated ε_r values are typical of peat, with 10% falling below 57 (range 24–40) and 90% greater than 82 (range 92–585). Physical properties that give ε_r values of above 82 are not possible [*Neal*, 2004]. Consequently, many of the velocities calculated using probes in this study cannot be caused by natural physical properties in peatlands. Conversely, when CMP velocities are converted to ε_r they fall within the typical ε_r range for peat (74, 69, and 65).

4.6. Explanation for the Difference in Peat Depth Obtained by the Two Methods

The GPR survey almost continuously had a notably sharp reflection throughout each profile (for example, Figure 5). In all eight peat cores extracted, LOI values, which are representative of organic matter, were high ($>$ 85%) until the peat to mineral interface (Table 2). It is very unlikely there would be anything else within the organic blanket peat deposits which would cause a sufficient contrast in physiochemical properties across the site to result in such a strong reflection other than the peat to mineral interface. Indeed the cores did not indicate any such physical layer other than then peat to mineral interface. Consequently, it is reasonable to assume that the peat to mineral interface has not been misinterpreted.

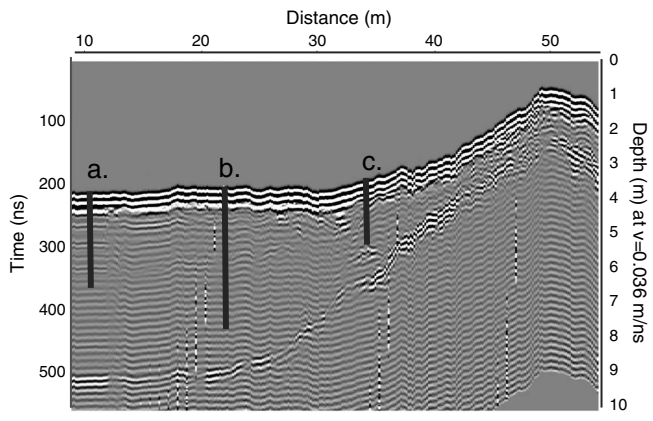

Figure 5. A GPR profile demonstrating the inconsistencies between GPR depth and manually probed depths (lines a, b, and c).

When the GPR tracks intersected, corresponding peat to mineral interface picks from differing GPR profiles were found to be in reasonable in agreement and close to the vertical resolution of the GPR survey (Section 4.2). As a result, inconsistent radar picks can be rejected as a source of the broader disagreement between the manual probes and GPR survey. In addition, at 25% of the sampling points, spatial variability in physical properties could not explain the disagreement in depth measurements observed (see section 4.5). Hence, for these locations, natural variability in peat physical properties can also be dismissed

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Table 2. Loss on Ignition (LOI) Values for Cores Extracted in Line With the GPR Transects (see Figure 1), Demonstrating the High Organic Content of the Site

Core	Mean LOI (%)	LOI Standard Deviation (%)	Bulk Density (g cm^{-3})	Median Von Post Class	Depth at Which Wood Is First Present (cm)
1	97	5	0.073	7.5	None
2	94	13	0.071	7.5	248
3	97	8	0.068	7.25	293
5	96	7	0.062	7.5	308
6	98	1	0.082	7.75	None
7	85	24	0.081	7.75	208
8	94	8	0.063	7.5	293

as a cause of disagreement. In cases such as these, where depth disagreement cannot be accounted for by quantifiable error (section 4.4), inaccurate probing remains the only explanation for disagreement. EMW velocities calculated using manual probe data and GPR TWTT are slower than would be expected in a typical peatland (see Table 1) and in many cases return nonphysical ε_r values (section 4.5). This suggests that probes were failing to meet the mineral layer and becoming obstructed within the peat. In some cases, it is possible to identify the feature impeding the manual probe within the GPR profile (for example, Figure 5, probe c). However, the 100 MHz GPR data have a vertical resolution of ~10 cm and decreasing horizontal resolution with depth (approximately 0.23 m, 0.48 meters and 0.61 meters at depths of 1, 3 and 4 meters respectively, assuming a central frequency of 91 MHz and ε_r of 69 [see *Neal*, 2004]).Therefore, if the diameter of features obstructing manual probes is below these resolutions, it may not be possible to identify them within the GPR radargram.

Evidence of the features obstructing manual probes was found within the Russian cores extracted from the site. Within a number of the cores, substantial pieces of wood greater than 3 cm in length were identified (Figure 6c and Table 2). These pieces of wood may have been large enough to impede a manual peat probe being inserted by hand but would not be visible on the radargram as they fell below the GPR resolution (see above). At each location where a peat core was extracted, peat depth was also measured using the manual probe (Figure 1). On 80% of occasions, the manual probe recorded was closer to the first occurrence of wood than the depth identified by the GPR trace (Figure 6).

A peat mass movement occurred in July 2012 on Keasden Moor which revealed a considerable amount of preserved birch within the peat mass (Figures 6a and 6b). Also, a large number of birch remains have become exposed as a result of erosion less than 500 m from the edge of the GPR survey. From this evidence, it is reasonable to assume that the large quantities of birch within the peat mass are the most likely cause of probes not achieving contact with the mineral layer. In many UK peatlands, remnants of former birch forests can be found within a peat profile [*Tallis and Switser*, 1983]. Moreover, many tropical peatlands are formed of woody peat [*Wüst et al.*, 2003] which may prevent probes from meeting the peat to mineral interface. Consequently, the problem of manual probes becoming obstructed before they meet the peat to mineral interface may not be isolated to Keasden Moor.

It may also be possible that at some sites, probes can extend into the sediment beyond the peat mineral interface. For example, *Rosa et al.* [2009] calculated mean EMW velocities of 0.040 m ns^{-1} and 0.039 m ns^{-1}, with standard deviations of 0.013 m ns^{-1} and 0.008 m ns^{-1}, using 175 manually probed depth measurements in two boreal peatlands. When converted to ε_r, these values fall within the range typical for peats (Table 3). However, the large standard deviations observed indicate a number values fall outside of the typical range (Table 3). High velocities and ε_r values lower than 57 were also identified in 6% of EMW velocities calculated using manual probes and TWTT at Keasden Moor. These values may result from probes extending into the mineral sediment, rather than the unusual physical properties of the peat. Probing into sediments below the peat seems a plausible explanation considering the process of terrestrialization and resultant soft gyttja layer found under many boreal peatlands [*Comas et al.*, 2004, 2005b; *Sass et al.*, 2010] and the thin clay layer formed in many Millstone Grit environments [*Holden et al.*, 2002]. The problem of determining the peat-mineral interface by probing when the sediments below the peat are soft has previously been noted by *Jol and Smith* [1995] and *Sass et al.* [2010].

5. Recommendations for Measuring Peat Depth

Two major implications of our research have been identified: (1) Manual probes do not always meet the peat to mineral interface, because probes have either become obstructed by artifacts within the peat body, such

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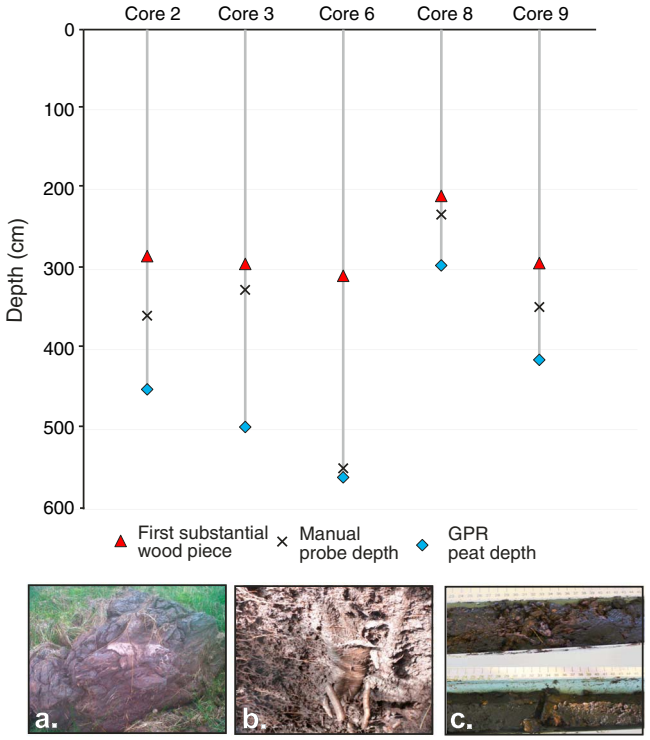

Figure 6. The depth of the manual probe and the measured GPR depth for each core containing wood (see Table 2), relative to the first occurrence of wood within each core. With examples of birch found with the peat at Keasden Moor: (a) large piece of birch washed out after the mass movement, (b) birch root within peat profile revealed in the mass movement, and (c) small lumps of birch within core profiles (note these took considerable man power to extract).

as wood, or have extended beyond the peat into the substrate, and (2) calibration of EMW velocity for GPR using manual probe depths can cause inaccuracy in the measurement of peat depth from GPR surveys. These findings have implications for the accuracy of peatland carbon inventories, global long-term carbon accumulation estimates, and surveys of peatland resources. Consequently, it is important to discuss best practice in measuring peat depth and the circumstances in which each technique should be applied.

5.1. Manual Probing

Some surveys of peat depth and structure are extensive and occur at a landscape (greater than 10,000 ha) to national scale. In situations such as these, it is not practicable to carry out GPR surveys. As a result, manual probing must be relied upon to generate inventories of peat depth. Where manual probing is adopted, there are two protocols which could be adhered to in order to ensure that the peat to mineral interface is met. First, peat depth probes could be adapted to sample a small amount of soil at the bottom of the probe, which then could be assessed to identify the transition from peat to mineral soil. This could be rapidly carried out in the field using methodologies such as Troel-Smith [*Troel-Smith*, 1955]. Second, replicate probing could be carried out at each sample point. It is suggested that probes are located at least 2–3 m apart in order to avoid large artifacts or clusters of wood (such as in *Parry et al.* [2012]). If these protocols are carried out, it would be reasonable to assume that the depth measurements are accurate and can still be reliably used as part of peatland resource estimates.

5.2. CMPs to Determine EMW Velocity

CMPs are considered the most accurate method for calibrating EMW velocity, as they provide a direct estimation using normal move-out hyperbola reflections from the GPR itself. However, the factors which determine EMW velocity, water content, and porosity are variable throughout individual peatlands, and as a result, the low number of CMPs typically carried out in peatland studies (Table 1) may not accurately represent the true average EMW velocity. At present, very little is understood about the degree of variability in porosity and water content both within and between peatlands [*Lewis et al.*, 2012], and consequently, it is not possible to quantify the extent to which this is an issue. However, in order to take account of any potential variability in ε_r across a peatland, CMPs must be carried out across areas of varying moisture content (such as in *Kettridge et al.* [2008]). Further work considering the number of CMPs required to accurately represent EMW

Table 3. Dielectric Permittivity Values Calculated Using Probed Velocity Values for Both This Study and *Rosa et al.* [2009]

	ε_r (Using Mean Velocity)	ε_r (Using Lower SD Velocity)	ε_r (Using Upper SD Velocity)	Number of Probes
Rosa et al. [2009] Site 1	56	123	32	110
Rosa et al. [2009] Site 2	59	94	40	65
This study	99	192	60	162

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velocity variability would considerably improve understanding of GPR depth survey accuracy. This is particularly important because recent development of integrated multioffset systems may enable greater numbers of CMPs to be gathered [*Gerhards et al.*, 2008]. In some cases, CMPs are not possible due to equipment-specific limitations, such as inseparable transmitting and receiving antennae. As a result, peat depth derived from manual probing are required for EMW calibration, and therefore, the manual probing protocols outlined above must be applied.

5.3. Problems of Single EMW Velocity Values

This study showed that using a standard velocity of 0.036 m ns^{-1} when carrying out GPR surveys resulted in between −8 and +17% error in depth measurement (see section 4.3). At present, most GPR studies on peatlands apply a single unvarying velocity across an entire study area [for example, *Warner et al.,* 1990; *Rosa et al.*, 2009; *Loisel et al.,* 2013]. Our study presents the broadest possible range of error associated with varying physical properties in peatlands. Although in a typical peatland, variability may not be as great as suggested by the modelling undertaken in our study, the water content and porosity will still be variable and will always introduce error, even if velocity has had site specific calibration. If advances are made in mapping water content and porosity, it may be possible to account for this error by applying CRIM to mapped values. This would substantially increase confidence when using GPR to map peat depth.

6. Conclusions

A number of methodologies exist for the estimation of peat depth and the calibration of GPR EMW velocity. Each methodology has strengths, such as the simplicity and low cost of manual probing and the high resolution afforded by GPR, and can be used for estimation of peatland resources, carbon storage, and rates of carbon accumulation. However, this paper has identified that an element of caution must be applied when estimating peat depth for both manual probing and GPR depth estimates. Manual peat probes may not successfully meet the peat to mineral interface and methodologies for the calibration of EMW velocity when using GPR can introduce error. We recommend that as standard practice, manual probing should be replicated and regular checks made to ensure that probing samples the peat to mineral interface, to confirm that the true peat depth has been recorded. Manual probing and/or CMP determinations are used to calculate EMW velocity in GPR surveys of peat depth. If manual probing methods are improved, as described in section 5.1, this will improve the more continuous GPR depth data collection. For CMP measurements, these should be carried out across varying moisture contents across the peatland being surveyed and the potential causes of error should be thoroughly reviewed for each individual peatland surveyed to eliminate a considerable amount of error when estimating peat depth.

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