An integrated geophysical and GIS based approach improves estimation of peatland carbon stocks.

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Abstract:

Estimations of peatland carbon stocks often use generalised values for peat thickness and carbon content. Ground penetrating radar (GPR), a rapid technique for field data collection, has been increasingly demonstrated as an appropriate method of mapping peat thickness. Light Detection and Ranging (LiDAR) data as a method for understanding peatland surface elevation are also becoming more widely available. Reliable mapping and quantification of site-specific carbon stocks (e.g. upland raised bogs) is therefore, becoming increasingly feasible, providing a valuable contribution to regional, national and potentially global carbon stock assessments. This is particularly important because raised bogs, such as those found in South Wales are considerable carbon stores. They are, however, susceptible to climate warming owing to their southerly location within the UK. Accurate estimates of peatland carbon stocks has broader importance because world-wide

peatland carbon stores are significant and threatened by climate change, posing a substantial challenge not only due to climate feedbacks if this stored carbon is released into the atmosphere, but also the impact on the other ecosystem services that they provide.

Here, we assess the value of an integrated GPR, LiDAR and Geographic Information System (GIS) approach to improve estimation of regional carbon stocks. We apply the approach to three ombrotrophic raised bogs in South Wales, UK, selected for their conservation value and their topographically-confined raised bog form.

GPR and LiDAR are found to be well suited, respectively, to mapping peat thickness at bog scale and surface elevation, thus allowing surface and basal topographies to be evaluated using GIS. In turn, this allows peat volumes to be estimated. For the first time, we record values between 55,200 m^3 and 163,000 m^3 for the sites considered here.

The greater confidence in these peat volume estimates results from the ability to calibrate the GPR velocity using a depth-to-target calibration with peat cores extracted at locations encompassing the deepest bog area. Peat thickness is mapped at the bog scale with near centimetre precision, improving the robustness of subsequent volume calculations and our understanding of the contribution of these small but numerous sites to regional carbon stocks. Our evaluation shows that GPR corresponds well with conventional manual probing but is minimally invasive and therefore less disturbing of sensitive peatland sites, while also offering improved coverage and spatial resolution with less time and cost.

In combination with measured bulk density and organic carbon contents, these peat volumes allow carbon stocks to be estimated with greater confidence compared to conventional approaches, having values between 2,181 ±122 tonnes carbon and 6,305 ±351 tonnes carbon at our three sites.

Keywords: ground-penetrating radar; peat; bog; carbon stock; LiDAR; GIS

1. Introduction

Terrestrial carbon stores are considerable. Peatlands in particular, whilst only covering ~3% of the earth's surface, account for approximately one third of all soil carbon storage (Gorham, 1991; Yu et al., 2011). In the UK, peatlands in their various forms (blanket bog, raised bog and fens) account for almost 10% of the land area (approximately three million hectares) and store approximately 3.2 Gt of carbon (Bain et al., 2011). The UK BEIS Emissions Inventory for Peatlands project estimated that there are 90,000 ha of peatlands in Wales (Evans et al., 2017); however, roughly two thirds are thought to be in a degraded state.

Emissions from damaged peatlands are of global significance. Peatland landscapes that have been drained or experience fires are estimated to release 1.3 Gt of CO_2 annually, this contributes 10% of greenhouse gas emissions from the land use sector (IUCN, 2017) and constitutes a major part of national greenhouse gas emissions in many countries (Joosten et al., 2012). The Kyoto Protocol of 2008; an agreement within the United Nations' (UN) Framework Convention on Climate Change and the 2012 Doha Amendment, committed its parties to internationally binding greenhouse gas emission reduction targets (United Nations, 2012). Accordingly, updated international carbon accounting rules mean that peatland soils, and specifically changes in carbon stocks as a result of activities related to wetland drainage and rewetting, can be voluntarily considered for reporting of CO_2 emissions (Blain and Murdiyarso, 2013).

In addition to emissions, peatland carbon losses can also occur as dissolved organic carbon and particulate organic carbon. Accurate assessment, including improved measuring, reporting and verification of the global peat-carbon store is therefore necessary to support governmental inventories and also for the purpose of informing global climate change models, including for the prediction of potential positive climate feedbacks from degraded peatlands (Gallego-Sala et al., n.d.; Gorham, 1991)

Sustainable management and restoration of peatlands is one of the most cost-effective ways to mitigate climate change by reducing greenhouse gas emissions and minimizing carbon loss from peat soils (Joosten et al., 2012). In recognition of this, the Welsh Government has prioritised an ambitious programme to ensure that all peatlands supporting semi natural habitats are under active management by 2030 and are aiming for 95% of Wales' peatlands to be in 'good' condition by 2040 (Welsh Government, 2019a, 2019b, 2019c). Peatland restoration (involving the many techniques which aim to restore ecohydrological function such as blocking drainage ditches and sphagnum planting) is required in order to ensure the future resilience of these habitats and the ecosystem services they provide including; the provision of drinking water, surface water attenuation, carbon sequestration and storage, and the provision of a landscape of recreational and cultural value (Bain et al., 2011; Grand-Clement et al., 2013; Joosten and Clarke, 2002).

A significant challenge to peatland management and policy development, however, is that regional carbon estimates for peatlands are often lacking and can contain inaccuracies due to the inconsistent and wide ranging methodologies employed, as well as the sometimes inappropriate use of published estimates rather than physically measured data (Parry et al., 2012; Parsekian et al., 2012; Petrokofsky et al., 2012; Yu, 2012). For example, over the last 50 years numerous estimates of UK peatland carbon storage have been published, ranging from around 3 Gt C to 7.8 Gt C (Billett et al., 2010; Bradley et al., 2005; Cannell et al., 1993; Lindsay, 2010; Milne and Brown, 1997). These inconsistent figures are largely a result of the different definitions of peat soils and methodologies used across the different regions of the

UK and the use of generalised estimates for peat thickness, bulk density and carbon content (Charman, 2002; Joosten and Clarke, 2002).

Carbon accounting in particular is further hampered by limited data on the key variables required for peatland carbon stock assessments, including fine-spatial scale mapping of peatland topography and accurate estimates of peat extent, thickness, peat bulk density and carbon content (Carless et al., 2019; Gatis et al., 2019). Historically, national carbon estimates for peat soils in the UK have been based on sparse field measurements and whilst studies such as Evans et al. (2016) provide data for these peat characteristics and carbon stock values for peat profiles from a Welsh site, it remains that detailed carbon stock assessments of Welsh peatlands are rare. Furthermore, the sites studied by Evans et al., (2016) were lowland fen (minerotrophic) sites and the applicability of these values to raised bog (ombrotrophic) sites, as investigated in this study, is limited due to differences in peat properties (e.g. bulk density) and ecohydrological functioning. The 2007 ECOSSE report (Smith et al., 2007) provides an estimation of the total carbon stored in peat and organo-mineral soils across Wales, being almost 0.2 Gt C. This was higher than any previous estimates (e.g. Bradley et al., 2005) due to the inclusion of peat greater than 1 metre in thickness, modifications to bulk density values (predicted using regression equations) and the methods used to calculate areas (soil map units). The inclusion of deeper peats was an important recognition that peat thickness can be extremely variable. Raised bogs (an Annex 1 priority habitat listed in the EU Habitats Directive, (*European Commission, 2007*) for example, often develop in basins and can contain peats 4-10 m thick. Studies that previously only considered up to 1 metre peat thickness are therefore likely to have resulted in underestimations in carbon stock calculations (Holden and Connolly, 2011).

Understanding the carbon storage of organic soils is particularly important for South Wales as it is home to some of the most climatically marginal (southerly) and most vulnerable ombrotrophic raised bogs in the UK, which have also suffered from excessive grazing pressure, fires and industrial pollution in the past. Accurate quantification of the extensive Welsh peatland carbon store is further required as it may be amongst the first to be affected by future climate warming (Gallego-Sala et al., 2010).

Only a small number of UK sites have been studied with the aim of quantifying carbon storage (Charman et al., 2013; Evans et al., 2016; Lindsay, 2010; Loisel et al., 2014; Ostle et al., 2009; Smith et al., 2007; Wellock et al., 2011). In this study, three raised bog sites in South Wales were assessed to (1) assist in alleviating the paucity of UK carbon stock estimates; (2) evaluate the scope of ground penetrating radar (GPR) measurements integrated with geographical information system (GIS) modelling in attaining peat thickness and volume estimates for the purpose of estimating peat carbon stocks; and (3) identify the suitability of this approach to regional upscaling of carbon stock estimates. This was achieved through the use of geophysical techniques (GPR) and remote sensing data (Light Detection and Ranging (LiDAR) Digital Terrain Model (DTM)). These datasets were integrated within a GIS (ArcGIS Pro) to extract peat volumes facilitating carbon stock estimates.

2. Material and Methods

2.1. Research site locations

The Brecon Beacons National Park, South Wales, hosts one of the most spectacular upland areas in Britain. The topography is varied with much of the park having an elevation over 300 m a.s.l. The National Park experiences a maritime climate which is locally modified by altitude and topography with a recognised climatic gradient across the park from the west to the east, a distance of ~ 80 km. The average annual rainfall in the western extreme of the park is over 2400 mm, whilst in the east rainfall is only 1500 mm (George, 1990; Pratt-Heaton, 1999). The geology of the park varies from north to south. The northern two thirds of the park is underlain by Devonian Old Red Sandstone. In the southern sector, a thin band of (Dinantian) Carboniferous Limestone runs from west to east, separating the Old Red Sandstone uplands from the southern Namurian Basal Grits. The southern limit of the park is bounded by the northern edge of the South Wales coal measures formation.

Three raised bog sites totalling approximately 12 ha within the Brecon Beacons National Park were studied (Figure 1). The study sites were chosen because of their particular conservation value (Natura 2000 designated sites) or allocation for future improvements/ restoration (e.g. New LIFE for Welsh raised bogs Project) as identified by the Brecon Beacons National Park Authority (BBNPA) and included 1) Mawnbwll du Mawr, 2) Gwaun Nant Ddu and 3) Waun Ddu bog within the Craig y Cilau National Nature Reserve (Figure 1). Each are classified as an ombrotrophic raised bog, which have developed within topographically confined basins and exhibit typical features of lagg, rand and shallow domes. Surface vegetation is dominated by graminoid and Ericeae species with expanses of sphagnum in wetter areas. All sites exhibit some degradation evidenced by areas of bare peat.

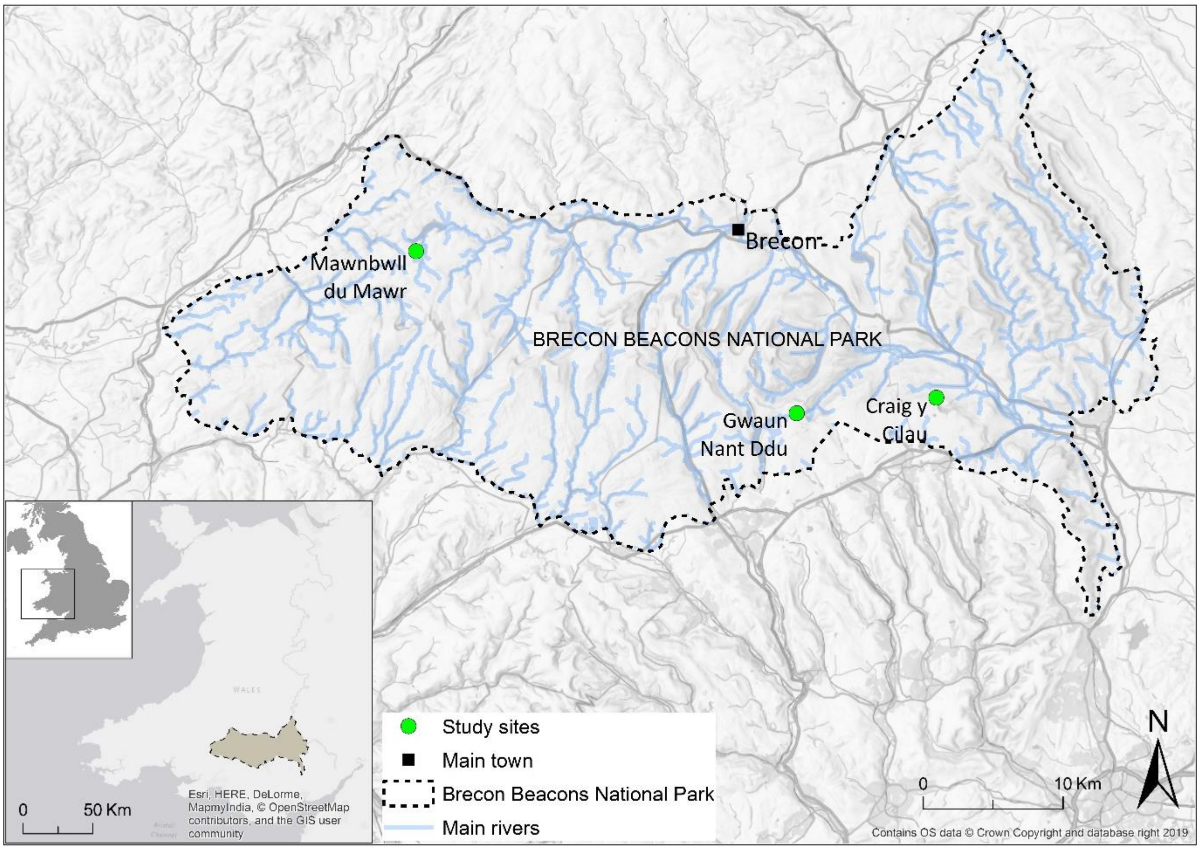


Figure 1. Location of study sites within BBNP, and the location of the park within Wales and UK (inset maps).

2.2. Background to methodological approach

Carbon stock estimates are most often achieved by calculating the carbon stored per unit volume of peat. This requires accurate figures for peat spatial extent, peat thickness and carbon density.

Peat spatial extent and thickness are most often approximated from aerial images or soil maps (Cannell et al., 1999; Cruickshank et al., 1998; Milne and Brown, 1997), meaning that regional averages for carbon stocks are based on limited physical sampling, or a generic peat thickness, such as 1 m, is applied (Petrokofsky et al., 2012; Yu, 2012).

The most common techniques for the collection of measured peat thickness data include coring, probing and digging trial pits. These point measurements are costly, being both time and person intensive (Gatis et al., 2019; Jol and Smith, 1995; Proulx-McInnis et al., 2013). Authors have noted that peat thickness data from manual probing (inserting a thin metal rod into the peat until resistance is felt) can also be prone to uncertainties leading to considerable over- and underestimation. Uncertainties are explained as caveats for the methods including those associated with the obliquity of the probe and the strength and subjectivity of the probe operator in identifying the peat-mineral soil interface. If the mineral substrate beneath the peat is unconsolidated material (e.g. in peatlands formed by the terrestrialisation of a small waterbody), then the probe can penetrate the soft lake sediments (gyttja) and a depth beyond the base of the peat will be recorded. Measurements may also be affected by the presence of obstacles (e.g. buried wood) which prevent the probe reaching the base (Doolittle and Butnor, 2009; Jol and Smith, 1995; Parry et al., 2014; Proulx-McInnis et al., 2013; Sass et al., 2010; Worsfold et al., 1986). Furthermore, these methods, which rely on interpolating between limited, manually-measured points may fail to capture sufficiently the fine-scale spatial variation in thickness, a result of variable underlying topography. Finally, being invasive methods they are unsuitable for many sensitive peatland sites, particularly if repeated assessments are required (Holden et al., 2002; Lindsay et al., 2014; McClellan et al., 2017; Parsekian et al., 2012; Plado et al., 2011).

In the 1980s, identifying the need to improve the speed and accuracy of peatland field survey, the Geological Survey of Finland investigated the use of GPR technology. The peat thickness data obtained was found to achieve greater detail than that gained by traditional means (drilling/coring methods) (Hänninen, 1992). Around the same time, Ulriksen (1982), also suggested that peat thickness from GPR were substantially more accurate than those achieved by drilling or probing (Jol and Smith, 1995). Since then, geophysical techniques (e.g. GPR, 2-D resistivity and electromagnetic induction) have increasingly been employed in peatland studies across Canada, Ireland, Finland, Sweden, Russia, the United Kingdom and the United

States. GPR is particularly effective and numerous peatland investigations have successfully employed it to gain detailed peat thickness data, as well as a greater understanding of peat volumes and internal stratigraphy (Doolittle and Butnor, 2009; Jol and Smith, 1995; McClellan et al., 2017; Parry et al., 2014, 2012; Parsekian et al., 2012; Ryazantsev and Mironov, 2018; Sass et al., 2010; Warner et al., 1990). Other studies have used GPR to assess gas accumulation and locate peat pipes (Comas et al., 2005; Holden et al., 2002; Sass et al., 2010).

GPR systems work by recording the two-way travel-time (TwTT) of electromagnetic (EM) waves. Specifically, the time it takes (in nanoseconds) for a pulse of electromagnetic energy, emitted from a transmitting antenna, to propagate into the subsurface and to be reflected back to a receiving antenna from a subsurface interface. Thickness is calculated by converting the measured TwTT to distance, using a known EM wave velocity. The velocity of the EM wave is directly dependent on relative dielectric permittivity (ε_r), a geophysical property strongly dependent on water content (Warner et al., 1990). The strength of the electromagnetic (EM) wave reflection depends on the contrast (reduction) in the volumetric moisture content between the peat and the underlying mineral soil. It is also dependant on the concentration of solutes in the pore water. Accordingly, GPR is generally more successful in investigations of ombrogenous peat (e.g. raised bogs and blanket peat) rather than minerogeneous (fen) sites because there are less inputs so a lower pH and basic cation content (Ca, Mg, Na, K) of pore water is found (Doolittle and Butnor, 2009; McClellan et al., 2017; Proulx-McInnis et al., 2013; Warner et al., 1990). Uncertainties in peat thickness achieved via the GPR method are attributable to the accuracy of the EM wave velocity used for the time-depth conversion and to the potential spatial variability in depth-integrated radar velocities. For example, some regions of the peatland might be drier than others and hence would likely have somewhat higher radar velocities than the overall wetter areas. Even where the peatland has comparable wetness, pore waters maybe more concentrated in ionic contents in some regions than others, which would also cause local/regional-scale differences in peat thickness estimates. It is therefore recommended that where possible, site specific velocity calibrations are completed through depth-to-target calibration via manual survey or common midpoint survey (CMP) (Comas et al., 2005; Parry et al., 2014; Proulx-McInnis et al., 2013; Rosa et al., 2009).

Studies which have sought to compare GPR with probing or coring methods have confirmed that the technique produces accurate data sets (less subjective, higher vertical and horizontal resolution, higher data density). GPR surveying is typically rapid and provides a continuous sub-surface profile along the survey transect at a resolution unachievable by traditional methods (Doolittle and Butnor, 2009; Jol and Smith, 1995; McClellan et al., 2017; Parry et al., 2014; Parsekian et al., 2012; Proulx-McInnis et al., 2013).

Through geostatistical interpolation (e,g, the process of ordinary kriging) the GPR derived peat thickness data is gridded (2m x 2m) and subsurface topographies plotted. When calculated volumes are combined with estimates of peat carbon density, more robust estimates of total carbon stock can be achieved (Fyfe et al., 2014; Parsekian et al., 2012; Rosa et al., 2009).

Here we use a combination of GPR and LiDAR data to constrain GIS-based calculations of carbon stocks, as detailed in the following sections.

2.3. Peat bog delineation

The lagg (stream) of a raised bog is the transition zone where runoff collects from the ombrotrophic (rain-fed) bog at its margin with the adjacent mineral soils (Howie and Meerveld, 2011). In this study, a combination of aerial images and LiDAR DTM data were analysed in ArcGIS. This allowed identification of the lagg stream at sites Gwaun Nant Ddu and Craig y Cilau, which were subsequently digitised to create a bounding polygon. At site Mawnbwll du Mawr the hydrology is more complex and the lagg stream was not easy to define from the aerial imagery. The bog perimeter was therefore established by interpreting bog to non-bog vegetation changes in aerial images and confirmed on site. Digitised boundaries were further validated in the field and in interpretation of the base peat reflection in the GPR data to ensure that in all cases the area bounded by the polygon and subsequently used for peat thickness and volume extraction, included only peat with a minimum thickness of 0.3 m as required for classification as a peat soil (Joosten and Clarke, 2002; Lindsay, 2010).

2.4. GPR surveying for peat thickness measurements

Peat thickness data for the three locations were collected by GPR survey. Data were acquired using a 100 MHz MALÅ Rough Terrain Antenna (RTA), an 'in-line' system involving a rugged, flexible cable, within which the transmitter and receiver electronics are separated by 2 m (see Figure 2). A single user can tow the cable behind them as they walk along the survey transect. The advantage of the flexible cable system is that good ground contact can be maintained even on rough, vegetated surfaces (Francke, 2012) and the cable slides continuously through the vegetation with minimal disturbance to it or the bog surface. Furthermore, continuous, rapid and fine-scale sampling (<1m spacing, depending on walking speed) can be collected.

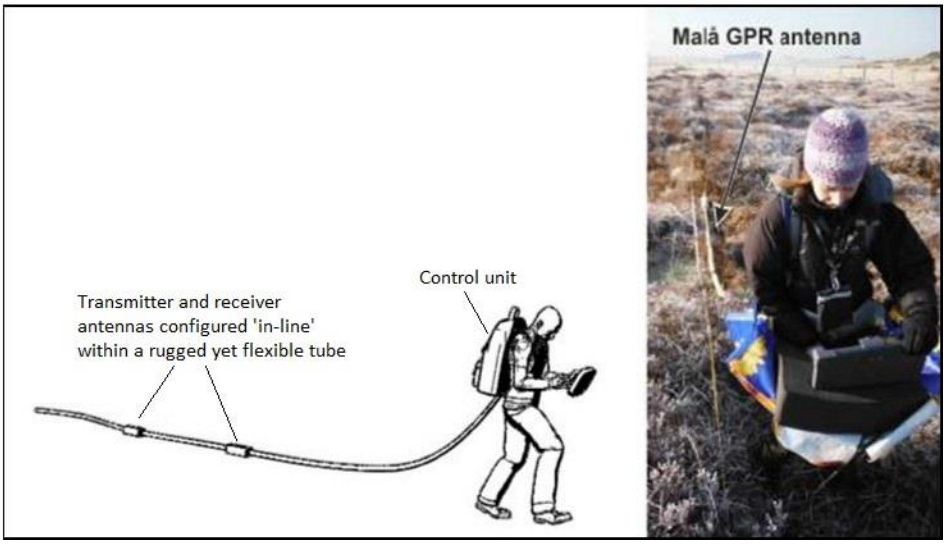
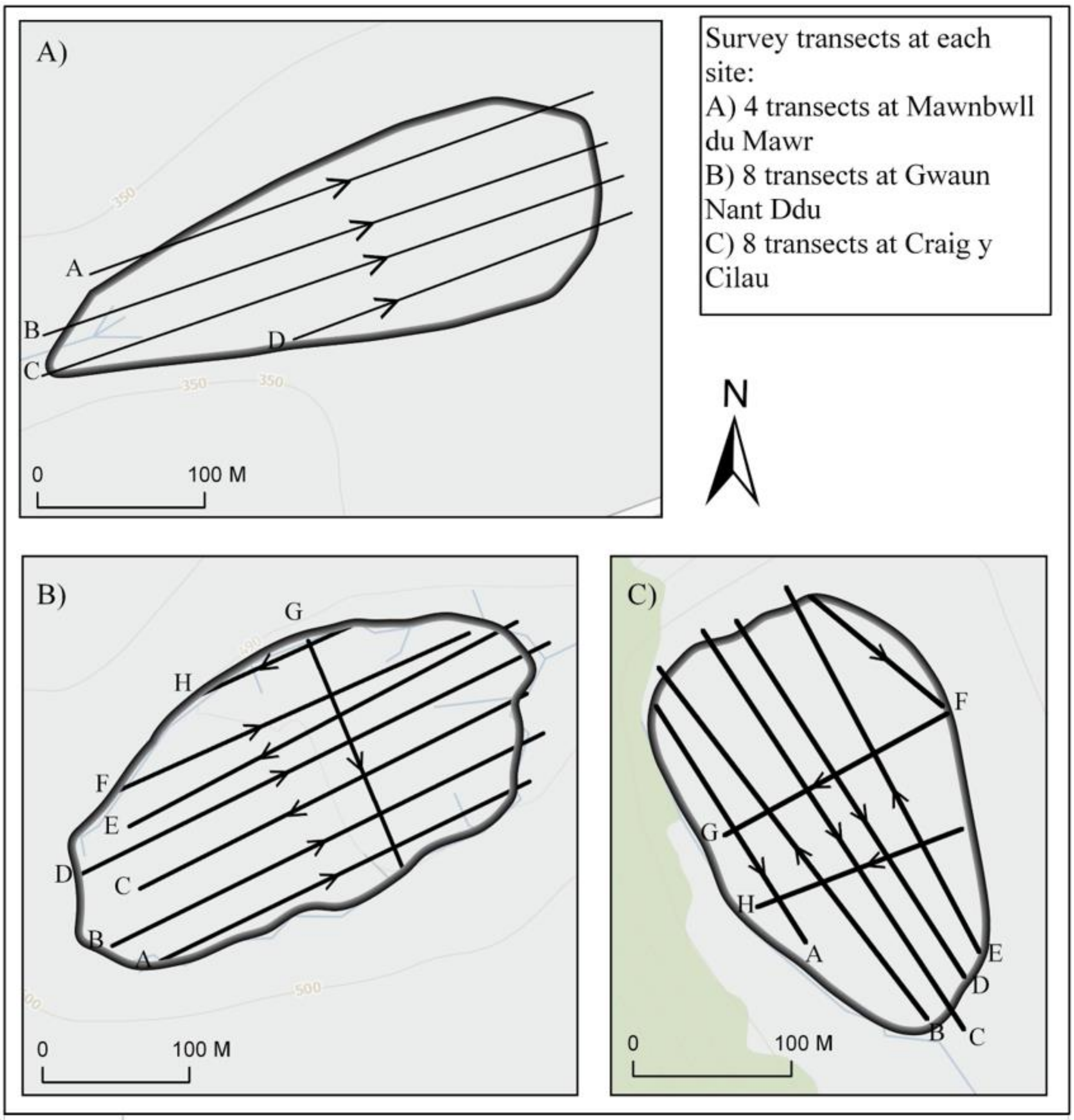


Figure 2. Illustration of Malå Rough Terrain Antenna (adapted from Francke, 2012) and its use in the field.

Over 5 km of GPR profiles were collected across the three sites. GPR survey transects following the long axis of the bogs were pre-marked with tapes and start and finish points logged in a handheld GPS (Garmin eTrex handheld unit) (Figure 3; Gwaun Nant Ddu and Craig y Cilau also having cross-transect surveys for validation). In a GPR survey the antennae are moved along the survey line (transect) and a series of traces (a record of the measured EM wave reflection) are collected at specific points along the line. Successive, multiple radar traces are taken at each sampling location which are automatically summed and averaged to produce one composite trace, reducing noise and improving signal coherence. The spacing between traces was 0.5 m (manually triggered) and 16 stacks were used for each trace, providing the best compromise between data quality and acquisition speed for our purposes. A window length of 500 ns was used, giving an expected sampling of 5-6 m for typical electromagnetic wave velocities of 0.0330-0.0385 m/ns through peat (Comas et al., 2005; Parry et al., 2014; Parsekian et al., 2012; Proulx-McInnis et al., 2013; Rosa et al., 2009; Sass et al., 2010).



	Transect length (m)							
Site	A	B	C	D	E	F	G	H
MDM	319	351.5	355	210	-	-	-	-
GND	280	330.5	333	350	300	276.5	185	132
CYC	182	275	300	298	260	129.5	175	145

Figure 3. GPR survey transect orientation and lengths at sites A) Mawnbwll du Mawr (MDM), B) Gwaun Nant Ddu (GND) and C) Craig y Cilau (CYC).

GPR data processing was undertaken using ReflexW software (Sandeimer, 2013) and was purposefully limited to application of a time-zero correction, a “dewow” filter and bandpass frequency filter. This sequence minimised processing artefacts while allowing a reflection to be identified in all GPR profiles (Figure 5), interpreted as the interface between the peat and the mineral soil. Although generally prominent, the reflection's signal-to-noise ratio is somewhat degraded in the deepest regions of the bogs; signal attenuation may have been enhanced owing to a basal layer of electrically conductive limnic clay, and in small sections by in-wash of more mineral sediments at the edges of the bogs. Consequently, with the exception of some short sections of transects on Gwaun Nant Ddu and Craig y Cilau, the onset of the basal reflection could be manually picked throughout the data volume, with a typical precision of ±1.5 ns (Gusmeroli et al., 2012).

Peat thickness was also evaluated using a manual probe at 74 locations (Mawnbwll du Mawr = 17, Gwaun Nant Ddu = 26, Craig y Cilau = 31), both to infill small gaps in the radar coverage (e.g., as a result of signal attenuation) and to provide initial calibration of GPR velocity estimates for conversion of TwTTs to peat thicknesses. Manual probing was completed following the standard method of inserting rods until resistance is felt. Resistance is assumed to be the peat-mineral interface with the depth at which this is encountered being recorded as the peat thickness (Parsekian et al. 2012). The location of each measurement point was recorded with a hand-held GPS. Assuming that the probe had reached the base of the peat, comparing the measured thickness to the TwTT in the GPR profiles data implied a preliminary radar velocity of 0.0343 m/ns, later refined following comparison to core data (see next section). An independent estimate of GPR velocity using, e.g., common midpoint survey methods (Huisman et al., 2003) was not possible in this study, given the fixed offset between the transmitter and receiver in the RTA system.

2.5. Peat core selection, sampling and analysis

The thickest peat sections at each site were identified from our radargrams, allowing targeted core sampling. A master core was extracted from each site for laboratory analysis of bulk density and carbon content. Using a Livingstone piston corer with a 5 cm diameter, stainless steel barrel, cores representing the total peat thickness were recovered from Gwaun Nant Ddu and Craig y Cilau sites. At Mawnbwll du Mawr, however, the core failed to achieve the full known thickness of peat due to resistant layers which could not be penetrated despite multiple efforts.

For peat analysis, cores were sampled at 4 cm resolution and bulk density estimated from subsamples of known volume, dried at 105 °C. Loss-on-ignition was calculated for every subsample using standard methods (Chambers et al., 2011) to estimate percentage organic matter content, and calibrated by direct measurement (via elemental analysis) of total organic carbon of a selection of samples (n=116).

In addition to providing material for bulk density and carbon analyses, LOI analysis of the core identified the depth at which the peat - mineral soil interface occurred, facilitating improved velocity calibration for the depth conversion of base-peat travel-times identified in the GPR data. The calibrated GPR velocity is 0.0352 ± 0.0005 m/ns based on the two study sites at which the full thickness of peat was achieved, where ±0.0005 m/ns is the standard error resulting from our assumption of a 5 cm nominal ambiguity in identifying a sharp contact at the transition from organic peat to limnic clay. This represents a ~2.5% increase over the initial velocity estimated from the probing (0.0343 m/ns) (see section 2.4) and lies squarely within the range of typical GPR velocities for peat (0.0330-0.0385 m/ns) (Proulx-McInnis et al., 2013; Rosa et al., 2009; Theimer et al., 1994). This velocity (0.0352 ± 0.0005 m/ns) was therefore taken as the calibrated ground-truth throughout all subsequent volumetric assessments.

2.6. Peat thickness mapping and calculation of peat volumes in GIS

The 2m resolution LiDAR composite data from aerial surveys flown in November 2012 were provided free of charge under a non-commercial use licence, by the Geomatics Group (Environment Agency, 2013). Data pre-processed into Digital Terrain Models (DTM) were provided in 1 km^2 tiles with an average vertical accuracy of ±15 cm and average horizontal accuracy of ±40 cm.

Using a three-step workflow in ArcGIS (Figure 4), LiDAR DTM and GPR data were used to generate (i) a peat surface topography layer, by extracting relevant surface elevation data (m above sea level) from the DTM data; (ii) a peat basal topography layer, by interpolating peat thicknesses (established from our GPR data) to a 2 x 2 m grid using the Kriging Geostatistical Analysis tool in ArcGIS (Dallaire and Garneau, 2008; Goovaerts, 1997; Zeng and Huang, 2007) and subtracting the values from the peat surface layer (i) to produce a basal topography layer as elevation (m above sea level); and (iii) a peat volume estimate by subtracting peat basal topography from surface topography using the ArcGIS Cut/Fill tool (Price, 2002). This was repeated for each of the three sites.

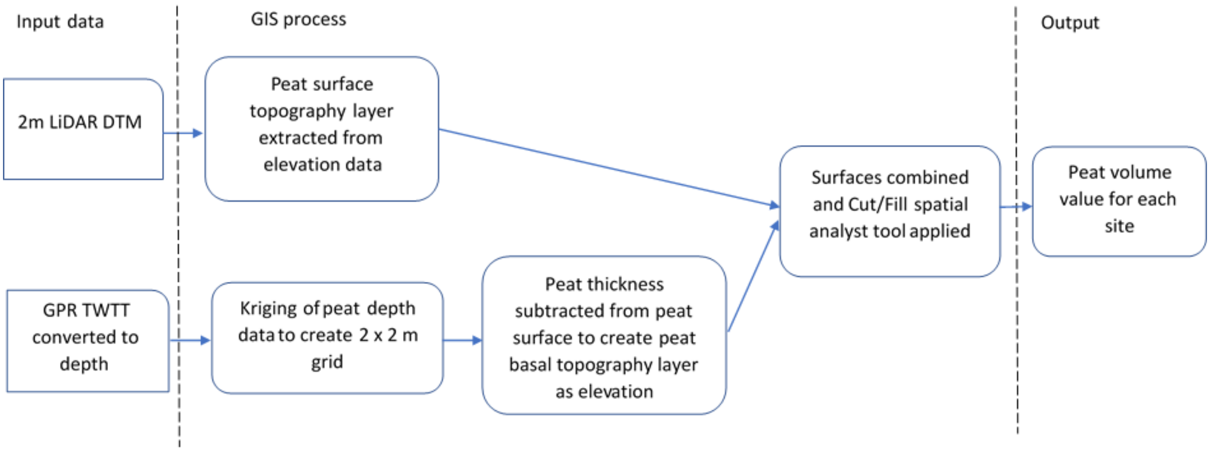


Figure 4: 3-step workflow in GIS to achieve peat volume calculations

2.7. Estimation of carbon stocks

As figures for the total volume of peat in a peatland site are relatively rare, calculations of carbon stocks often ignore this parameter, preferring to calculate a carbon per unit volume (e.g. per m^3) and multiplying this by area and thickness (often limited to 1 m). In this study however, LiDAR and GPR data were combined to model the peat basin volume. It was therefore possible to calculate carbon stocks from the mass of organic matter within each site. The mass of organic matter (kg) was established from peat volume (m^3) and bulk density (g cm^3), using equation (1):

$$Mass_{om} = V_{i \times \rho_i} \quad (1)$$

Where $Mass_{om}$ is the mass of organic matter (peat); V_i is the volume of peat for site $_i$ and ρ_i is the measured bulk density for the site.

Carbon stock (C_{stock}) (kg C) for each site is then calculated from the product of the organic matter mass ($Mass_{om}$) and the fraction of organic matter that is carbon (OM_c) established from the calibrated LOI data, following equation (2):

$$C_{stock} = Mass_{om} \times OM_c \quad (2)$$

2.8. Explanation of estimation of uncertainties

In order to estimate the uncertainty in the calculation of carbon stock, the method of error propagation for multiplication of measured properties was applied (Bevington and Robinson, 2003). The uncertainties in the measured variables; volume (m^3) (calculated using the ± 0.0005 m/ns standard error in depth) and density (g cm^3) were carried over to determine the uncertainty in the dependent variable; mass (kg).

To establish the effect that the uncertainties in both volume and density have on the calculated mass, the following equation (3) is applied:

$$\delta m = M \times \sqrt{\left(\frac{\delta v}{V}\right)^2 + \left(\frac{\delta d}{D}\right)^2} \quad (3)$$

Where, M is mass; V is volume; D is density; δm is the uncertainty in mass; δv is the uncertainty (±1σ) in volume and δd is the uncertainty (±1σ) in density. The uncertainty in the peat mass (δm) is then carried through and combined with the uncertainty in the measurement of organic carbon in order to present an error estimate for the site specific carbon stock value.

3. Results and discussion

3.1. Geophysical results - peat thickness

Basin depth, and therefore peat thickness, was found to vary both within and between sites. A summary of the maximum and mean depth to the peat-mineral soil interface recorded for each site are reported in Table 1. The maximum thickness of peat was 5.48 m, recorded at Gwaun Nant Ddu.

Table 1 Maximum and mean peat thickness recorded, assuming a GPR velocity of 0.0352 m/ns.

Site	Area (ha)	Max thickness (m)	Mean thickness (m)
Mawnbwll du Mawr	3.0	3.91	1.81
Gwaun Nant Ddu	4.8	5.48	3.41
Craig Y Cilau	3.8	5.39	2.66

The shallowest mean peat thickness was measured at Mawnbwll du Mawr. Here, the peat surface showed a subtle raised or domed area, as often seen with well-developed ombrotrophic bogs. The raised area was not central however, instead located in the northwestern region of the bog (Figure 7). Analysis of the GPR depth data confirmed that the dome was located above a shallow basal depression where the thickest peat was recorded.

Gwaun Nant Ddu demonstrated a more typical raised bog profile, with an obvious and well-defined lagg, rand and dome. The GPR data illustrated that the peat had developed in a topographically confined hollow with the dome located relatively centrally over it. Peat thicknesses were highly variable and some of the thickest of all sites were recorded here.

The GPR data from Craig y Cilau exhibited considerable small-scale variation in basal topography, illustrated by undulations in the basal reflection. A possible explanation for this is debris and boulders from the limestone escarpment which bounds its northern and western edges, falling into the basin prior to peat formation. Even so, a depression was recorded in the basal topography and a distinct dome formed the surface, confirmed by achieving greatest peat thickness measurements in this location.

3.2. Validation of peat thickness from GPR using peat core data

At Gwaun Nant Ddu and Craig Y Cilau, cores of 489 cm and 444 cm length were collected, respectively. The measured depth of peat from these two cores were found to be close to the peat depths measured by the GPR (Figure 5) and suggests that the assumption of using the same GPR velocity for both sites is acceptable.

Additionally, a comparison of the GPR data with the loss-on-ignition data from peat core analysis gave further confidence that GPR is effective at recording the base of peat. At both these sites the coring had sampled fully the ombrotrophic peat and extended into the underlying mineral layer of the bog. This is evidenced by a significant drop in % organic matter in the LOI data. Accordingly, the depth at which a strong reflection was recorded in the radargram was shown to correspond well with the depth at which an increase in the mineral content of the peat was seen.

We were able to conclude therefore that GPR provides an appropriate method for identifying the base of the peat and the location of the greatest thickness of peat for core extraction.

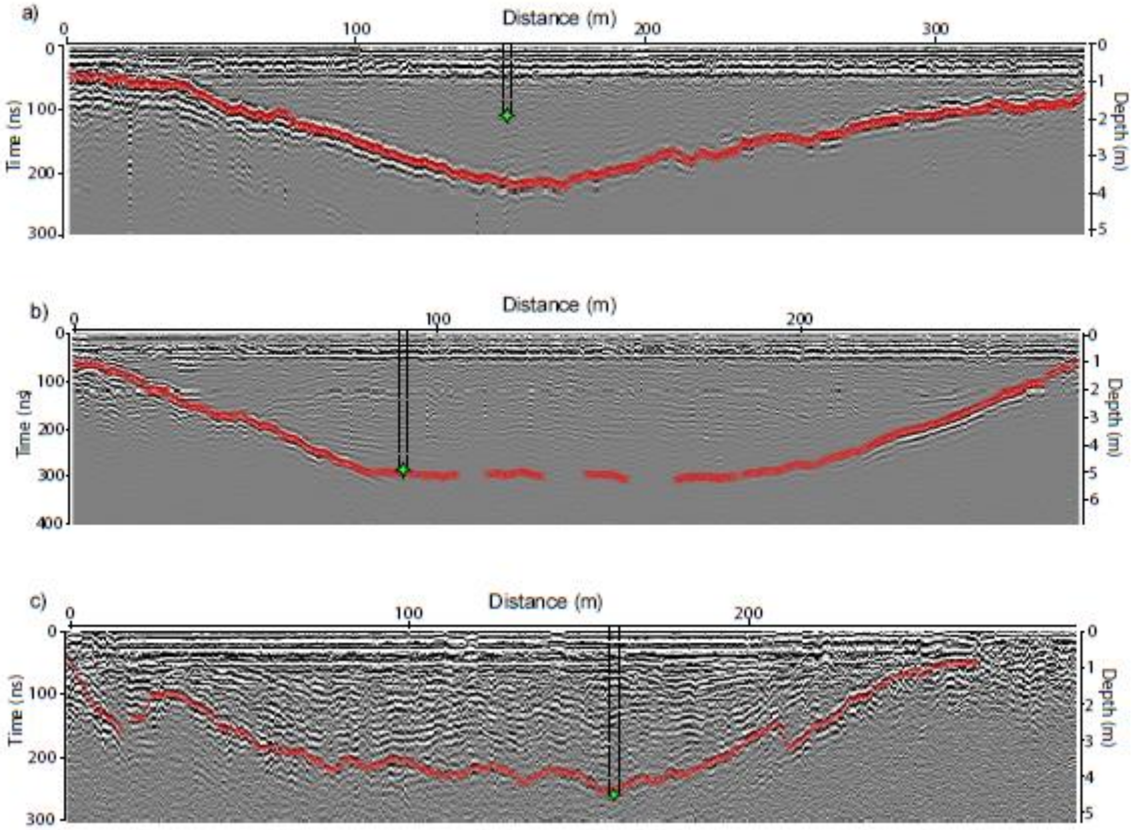


Figure 5. Location and depth of peat core plotted against radargram for a) Mawnbwll du Mawr, b) Gwaun Nant Ddu and c) Craig y Cilau.

Peat thicknesses from manual probing and GPR correlated well with each other (N=74, r-value = 0.85, p value = <0.001). Notwithstanding, manual probing was found to both over- and underestimate peat depths, when compared to GPR (Figure 6), likely due to difficulties identifying the peat-mineral boundary and being subjective to the probe user. Manual probing is also time consuming in achieving large sample sizes (for example to complete sampling at high spatial resolution (0.5 m – 1 m spacing) along multiple 100+ m transects), compared to GPR.

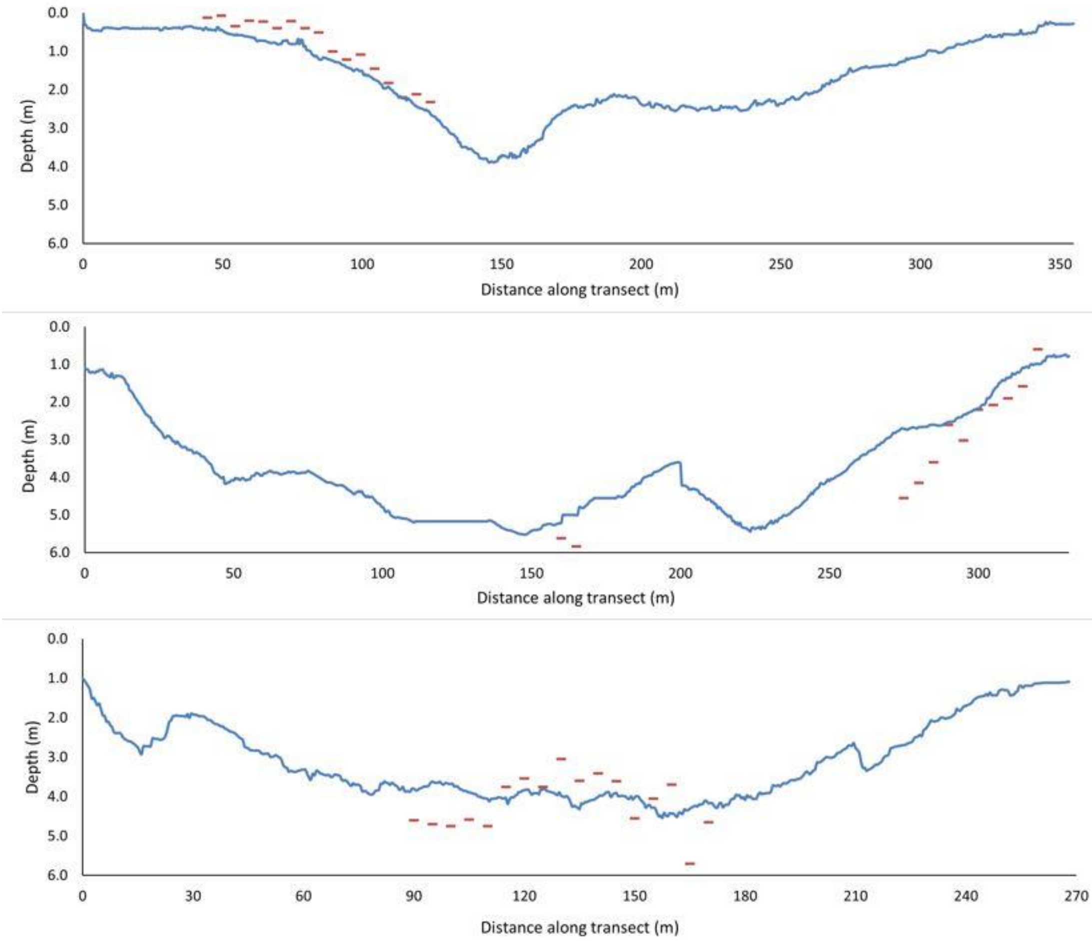


Figure 6. Comparison of probing depths (red dashes) plotted against GPR peat base depths (blue line) for selected GPR transects. A) Mawnbwll du Mawr, Line 3, B) Gwaun Nant Ddu Line 2 and C) Craig y Cilau Line 4. Note the different vertical scales in the panes.

3.3. Peat thickness maps (kriging) and calculation of peat volumes in GIS

Figure 7 shows contour plots of peat thickness at each site, subsequently used to evaluate volumes (Table 2). The peat volume was calculated by converting GPR TwTT to thickness using a velocity of 0.0352 ± 0.0005 m/ns. The volume of Gwaun Nant Ddu bog is estimated at 163,000 (±2285) m^3, with Mawnbwll du Mawr and Craig y Cilau showing smaller volumes of 55,000 (±773) m^3 and 101,000 (±1411) m^3, respectively.

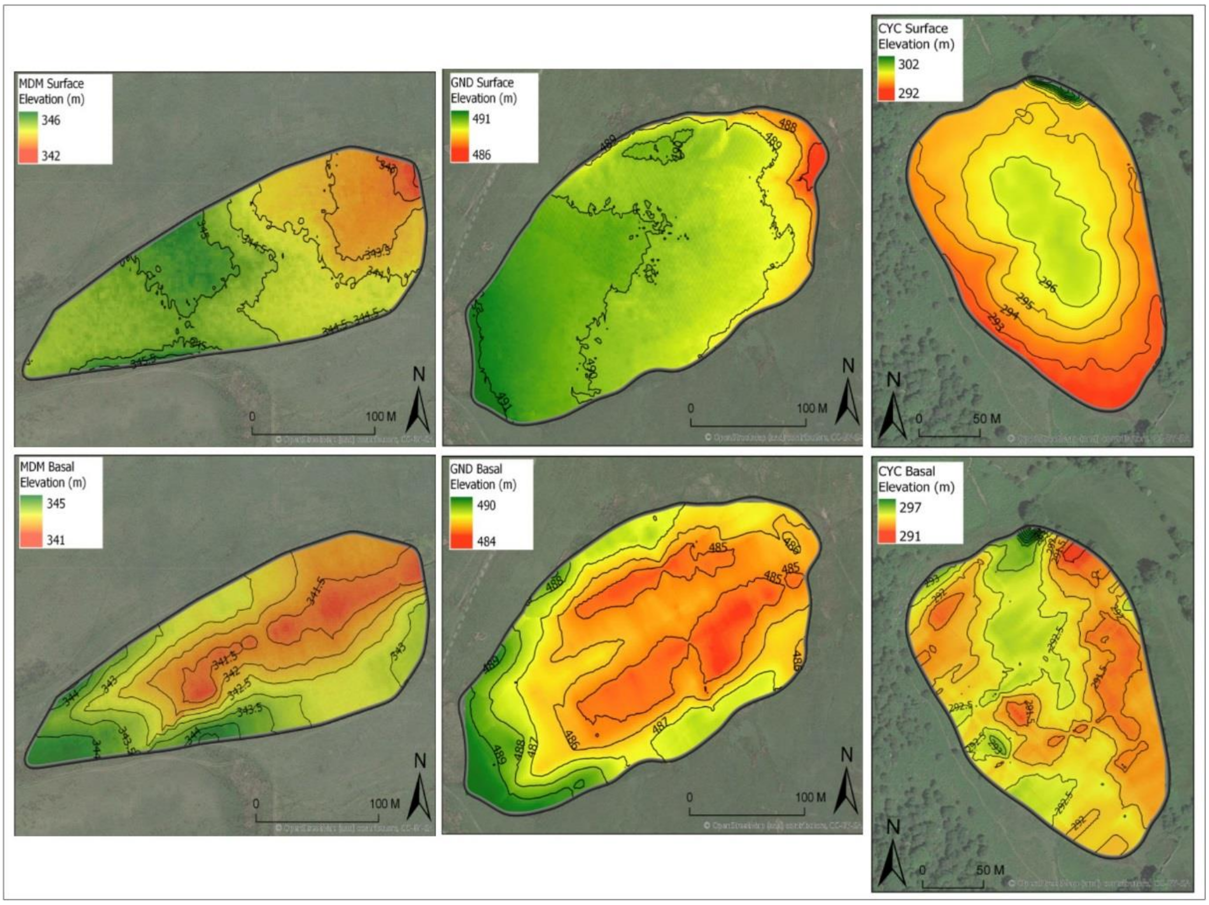


Figure 7. Example surface elevation contour maps (Upper images) and sub-surface elevation contour map (Lower images) for sites A) Mawnbwll du Mawr, B) Gwaun Nant Ddu and C) Craig y Cilau. Background image: Google Maps Hybrid.

3.4. Laboratory analysis – bulk density and carbon content

Bulk density and total organic carbon are presented in Table 2. Our measured mean bulk densities (~ 0.07 - 0.08 g cm^{-3}) are within the range reported for ombrotrophic peats of northern peatlands (0.07 - 0.15 g cm^{-3}, Lindsay, 2010). They also compare well to figures presented for basin peat >1m in Scotland (0.09 g cm^{-3}, Chapman et al., 2009; Milne and Brown, 1997) and a Welsh upland site (0.08 g cm^{-3} at Plynlimon-Hafren, Smith et al., 2007). Measured values for organic carbon content at our sites (~ 51.0 - 51.5%) are towards the upper end of typical values for northern peatlands (47 ± 6%, Loisel et al., 2014) and within the range quoted for basin peats in Scotland (48.6 ±1.1 % for 0.3 – 1 m peat depths and 60.8 ± 3.4 % for >1 m peat depths, Chapman et al., 2009).

3.5. Carbon stock estimation

Site Gwaun Nant Ddu returned the largest total peat (organic matter) mass with 12,200 tonnes which, when converted using carbon content, was calculated to represent a total carbon stock of 6310 tonnes of carbon. Craig y Cilau was calculated to contain 8,070 tonnes of organic matter, equating to a mean carbon stock of 4,110 tonnes of carbon. The smallest site of the study, Mawnbwll Du Mawr, had an organic matter mass of 4,250 tonnes, equivalent to 2,180 tonnes of carbon.

Table 2. Summary table of peat analysis for each site – bulk density (g cm^{-3}), organic matter (%), carbon content (%) and carbon density (g C cm^{-3}) and calculated peat volume (m^3) and carbon stocks (t C). Values in parenthesis are standard errors for all but Carbon Stock which are errors based on propagation of uncertainty (see section 2.8).

	Bulk Density g cm^{-3}	Mean organic content (%)	Mean carbon content (%)	Mean carbon density (g c cm^{-3})	Mean peat volume (m^3)	Peat mass (t)	Carbon stock (t C)
Mawnbwll Du Mawr	0.077 (±0.002)	97.8 (±0.220)	51.3 (±0.210)	0.04 (±0.001)	55,202	4,250	2180 (±122)
Gwaun Nant Ddu	0.074 (±0.001)	96.5 (±0.347)	51.5 (±0.160)	0.04 (±0.001)	163,249	12,200	6310 (±351)
Craig y Cilau	0.080 (±0.001)	96.1 (±0.302)	51.0 (±0.131)	0.04 (±0.001)	100,811	8,070	4110 (±231)

4. Discussion and conclusions

We have demonstrated that combining peat thickness data from GPR survey and surface elevation data from LiDAR in a GIS can improve characterisation of peatland sites and peat volumes and therefore carbon stock estimations in a UK region that may respond particularly rapidly to climate warming. GPR has at least three critical advantages compared to more conventional manual probing in that it is (i) non-invasive and thus avoids disturbing the sensitive bog vegetation or peat surface; (ii) rapid so that entire bogs can be surveyed in a fraction of the time required for probing at the bog scale; and (iii) relatively reliable in mapping peat thickness as a continuous lateral reflection across the sites, facilitating peat-volume estimates with lower uncertainty than those calculated from lower spatial resolution data interpolated from probing measurements, which are known to both over- and underestimate peat thickness.

GPR data analysis identified the thickest areas of peat from which cores were subsequently extracted. Laboratory analysis of the peat cores (LOI) allowed accurate identification of the depth of the peat-mineral soil interface, which served to ground-truth the base-peat GPR reflection. The radar propagation velocity through peat was subsequently calibrated, yielding a value of 0.0352 ± 0.0005 m ns^{-1} that falls squarely within the cumulative velocity range reported in other extensive, worldwide peatland studies (Comas et al., 2005; Parry et al., 2012; Parsekian et al., 2012; Proulx-McInnis et al., 2013; Sass et al., 2010; Theimer et al., 1994). Once calibrated, GPR surveying facilitates peat thickness mapping with centimetre-scale precision (McClellan et al., 2017; Parry et al., 2014; Theimer et al., 1994).

GPR-derived peat thicknesses facilitated kriging of peat basal surfaces in GIS. These basal surfaces were then combined with a surface topography layer (LiDAR DTM) in ArcGIS to extract a peat volume, using the Cut/Fill analysis tool. This provided a uniquely detailed picture of peat basin morphology and volume of peat for these sites, from which we can calculate carbon content.

Bulk density and organic carbon content analyses were carried out for all three sites reported here, respectively yielding values of ~ 0.074 - 0.080 g cm^3 and ~ 51.0 – 51.5% that agree with other published data for UK peatlands (Chapman et al., 2009; Charman et al., 2013; Lindsay, 2010; Loisel et al., 2014; Smith et al., 2007; Wellock et al., 2011).

The overall carbon stock values for our three sites were calculated from the volume estimates and carbon analysis, yielding values of 6,310 ±351 t C for Gwaun Nant Ddu, 4,110 ±231 t C for Craig y Cilau and 2,180 ±122 t C for Mawnbwll du Mawr.

It is suggested that this novel combination of techniques could facilitate investigations of ombrogenous peatland sites, such as raised bogs or blanket peatlands, previously overlooked but which contain significant stocks of carbon when considered across wider regions. These sites are often sensitive and the subject of management plans but demonstrate degraded conditions. It is understood that healthy, actively peat-forming habitats function as carbon sinks, sequestering CO_2 via photosynthesis and due to limited decomposition of organic matter, transfer it into the soil carbon pool (Lal, 2008). Functioning peatlands can have a net long-term 'cooling' effect on the climate (Limpens et al., 2008; Yu et al., 2011). Accordingly, peatlands are increasingly recognised for their importance in the global carbon cycle and due to becoming ever more threatened ecosystems. Our findings have provided a better understanding of carbon stored in specific sites and their contribution to national carbon stocks. This could provide additional knowledge for national management strategies and for safeguarding against future carbon losses to the atmosphere.

In conclusion, peat thickness, volume and carbon stocks have been modelled to a new level of detail useful for regional planning and management of these sensitive sites. Our new approach could be widely adopted to allow inclusion of raised bogs in regional scale peat carbon stock assessments. We recognise that the use of GPR may incur costs for purchase or rental of equipment, but these are outweighed by the potential reduction in costs from savings in time and person hours for detailed surveys. Furthermore, the increasing availability of 1m spatial resolution LiDAR data (through the UK Environment Agency National LIDAR Programme), for mapping of peat bogs and free, open-source GIS software mean this methodology can easily be applied to other UK sites. Many European countries also now have LiDAR DTMs openly available (e.g. Estonia, Finland, Norway, Sweden). However, in areas where LIDAR data is not available, we suggest that GNSS receivers in conjunction with the GPR survey (i.e. mount a roving GNSS antenna on the radar system and then postprocess those data relative to a base station), could provide surface elevation data of equally adequate vertical and planimetric precision. GNSS instruments are widely available on a global scale and hence this approach should almost always be feasible. In the rare case that it is not possible then a constant topographic value (e.g. 0 m) could be assigned to the peat surface but it must be borne in mind that this would only be appropriate for peat deposits with a flat surface topography at the survey site scale and will give a less accurate estimate of peat thickness and associated volumes.

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