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Mapping upland peat depth using airborne radiometric and lidar survey data

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ABSTRACT

A method to estimate peat depth and extent is vital for accurate estimation of carbon stocks and to facilitate appropriate peatland management. Current methods for direct measurement (e.g. ground penetrating radar, probing) are labour intensive making them unfeasible for capturing spatial information at landscape extents. Attempts to model peat depths using remotely sensed data such as elevation and slope have shown promise but assume a functional relationship between current conditions and gradually accrued peat depth. Herein we combine LiDAR-derived metrics known to influence peat accumulation (elevation, slope, topographic wetness index (TWI)) with passive gamma-ray spectrometric survey data, shown to correlate with peat occurrence, to develop a novel peat depth model for Dartmoor.

Total air absorbed dose rates of Thorium, Uranium and Potassium were calculated, referred to as radiometric dose. Relationships between peat depth, radiometric dose, elevation, slope and TWI were trained using 1334 peat depth measurements, a further 445 measurements were used for testing. All variables showed significant relationships with peat depth. Linear stepwise regression of natural log-transformed variables indicated that a radiometric dose and slope model had an $r^2 = 0.72/0.73$ and RMSE 0.31/0.31 m for training/testing respectively. This model estimated an area of 158 ± 101 km^2 of peaty soil > 0.4 m deep across the study area. Much of this area (60 km^2) is overlain by grassland and therefore may have been missed if vegetation cover was used to map peat extent. Using published bulk density and carbon content values we estimated 13.1 Mt. C (8.1–21.9 Mt. C) are stored in the peaty soils within the study area. This is an increase on previous estimates due to greater modelled peat depth. The combined use of airborne gamma-ray spectrometric survey and LiDAR data provide a novel, practical and repeatable means to estimate peat depth with no *a priori* knowledge, at an appropriate resolution (10 m) and extent (406 km^2) to facilitate management of entire peatland complexes.

1. Introduction

The inclusion of wetland drainage and rewetting in the United Nations Framework Convention on Climate Change (2012) has raised renewed interest in mapping peatland extents and depths; to provide better estimates of carbon stocks, monitor changes to peatlands and facilitate appropriate management (Aitkenhead, 2017; Biancalani and Avagyan, 2014). Moreover, it has been recognised that peatlands provide a range of ecosystem services (Grand-Clement et al., 2013) many of which are regulated throughout the full thickness of the peat - in particular, fresh water provision and climate regulation. As blanket peatlands are highly variable in depth (Bragg and Tallis, 2001) there exists an operational challenge to map peat depth at a sufficiently fine spatial resolution to capture the small-scale variability that is known to exist in blanket peat depth (cm's – m's) over the required spatial extents (m's – km's).

The two main methods currently used to measure peat depth are manual probing of the peat *in situ* and ground-penetrating radar (GPR). Peat probing is the more commonly deployed method due to its low cost and minimal equipment requirements (Akumu and McLaughlin, 2014; Beilman et al., 2008; Buffam et al., 2010; Holden and Connolly, 2011; Householder et al., 2012; Parry et al., 2012). Manual probing

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entails pushing a thin (~1.5 cm diameter) metal pole into the peat, at discrete spatial intervals, until resistance from the underlying soil/bedrock is felt. These point measurements are then commonly interpolated across large sites to produce peat-depth models (for examples see Akumu and McLaughlin, 2014; Householder et al., 2012). In contrast, GPR is a non-invasive proximal sensing technique whereby the two-way travel time of a pulse of high frequency energy reflected off the interface between the saturated peat and the underlying strata is measured (Davis and Annan, 1989). This delivers fine spatial resolution (mm to cm) measurements of peat thickness every 0.5 to 1 m along a transect typically tens to hundreds of meters in length (e.g. Comas et al., 2015; Lapen et al., 1996; Parry et al., 2014; Plado et al., 2011). A series of transects can then be interpolated to produce a peat depth map. Both probe and GPR measurements are labour intensive particularly when mapping peat depth over landscape extents, for example Parsekian et al. (2012) took 53 person hours to probe 0.095 km^2 on a 20 m grid and 30 person hours to cover the same area using GPR. Resultantly, the scale of blanket peat coverage across Dartmoor, UK (406 km^2) would preclude the use of both of these methods.

As an alternative to measuring peat depth *in situ,* some studies have modelled peat depth using remotely sensed data. Holden and Connolly (2011) modelled peat depth for the Wicklow mountains, Ireland using an exponential relationship with slope constrained by elevation (national DTM) and disturbance mapped using satellite imagery. Parry et al. (2012) also used exponential relationships with airborne Interferometric Synthetic Aperture Radar derived slope and/or elevation, this time constrained by previously mapped soil/vegetation units to model peat depth for Dartmoor. Rudiyanto et al. (2016) used Shuttle Radar Topography Mission derived digital elevation model to derive topography, slope, aspect, wetness index and distance to river metrics. They then applied a quantile regression function and cubist regression tree models to model tropical peat depth in Indonesia. In a more recent study of Indonesian tropical peat depths, Rudiyanto et al. (2018) applied machine learning to 37 potential covariates derived from satellite-based remote sensing data. They found elevation, radar images (a proxy for wetness), valley bottom flatness (indicative of areas of deposition) and distance to the nearest river to be the main controls on peat thickness. These models varied in resolution (30 m to 1 km) and coefficient of determination from 0.52 (Parry et al., 2012) to 0.97 (Rudiyanto et al., 2018) all showing the potential of modelling peat depths across larger extents. However, these models do not account for the underlying, and often complex topography commonly smothered by blanket bogs. In addition, they assume a direct relationship between peat depths and present accumulation rates controlled by topography, elevation, slope, aspect and wetness.

Estimates of peat depth are sometimes limited to areas previously defined as peatlands (e.g. Akumu and McLaughlin, 2014; Householder et al., 2012). The extent of which have been delineated by the presence of vegetation communities visible in aerial (e.g. Cruickshank and Tomlinson, 1990) and/or satellite (e.g. Aitkenhead, 2017) imagery. This assumes that peat is overlain by peat-forming vegetation communities, however, where peatlands have been subject to land management, peat may be overlain by non-peat forming vegetation (Connolly et al., 2007). To capture both actively forming and relic peats, it is imperative that any method to map peat depths are capable of including these areas of peat overlain by non-peat forming vegetation.

An emerging remote sensing method that has shown potential to map peat depth over landscape extents is airborne gamma-ray spectrometric survey. Gamma-ray spectrometers measure in the range 0.2 to 3 MeV, equivalent to a wavelength of 3×10^{-12} m, for geological interest (Minty, 1997). Potassium (K), Uranium (U) and Thorium (Th) in rocks and soils have naturally occurring radioisotopes (and daughter isotopes) that release gamma-rays with characteristic energy and intensity which can be detected by such airborne gamma-ray spectrometers (Minty, 1997). Radiation emitted from the underlying bedrock is attenuated (mostly incoherent scattering) by the overlying soils, the amount of attenuation is dependent on the thickness of the soil, porosity, saturation and density (Beamish, 2013a). Rawlins et al. (2009) noted the remarkably high absorbance of naturally occurring potassium by peatland soils in Northern Ireland. Using the same data, the extent to which total K, U and Th can be used to map peat was investigated by Beamish (2013a). He then extended this work to other areas in the UK comparing areas of mapped peat to radiometric dose (total P, U and Th) (Beamish, 2015, 2013b) noting considerable variation within a peatland. However, due to the high attenuation by saturated peat (90% of radiation attenuated by 60 cm of 80% saturated peat) the ability of radiometric data to map peat depth has been questioned (Beamish, 2013b). Despite this Keaney et al. (2013) showed the potential of radiometric data to update existing peat depth models by comparing the spatial patterning of airborne radiometric data to that of probed peat depths for a blanket bog and a lowland raised bog in Northern Ireland.

Herein we combine LiDAR derived metrics known to influence peat accumulation (elevation, slope, topographic wetness) with gamma-ray spectrometric survey data, shown to correlate with peat occurrence to investigate whether using two technologies (LiDAR and gamma-ray spectroscopy) with differing data content can be used more effectively in tandem to develop a novel peat depth model for Dartmoor.

2. Material and method

2.1. Study area

Dartmoor National Park lies in the southwest of England (Fig. 1a), it contains an extensive area of upland moor. Its maritime location and elevation (reaching 623 m above sea level) result in average annual precipitation of 1974 mm and a mean monthly temperature range of 0.8 to 17.7 °C. These conditions enable blanket bog, a globally restricted, and consequently important, habitat to form (Lindsay, 1995; Tallis, 1997). The area is also important regionally for drinking water provision and flow regulation as Dartmoor contains the headwaters of many rivers. The peatland not only stores carbon but also paleoarchaeological records (e.g. Fyfe and Woodbridge, 2012) and in some locations heritage assets e.g. burial cists (Jones, 2016) as well as providing ecosystem services (Millennium Ecosystem Assessment (https://www.millenniumassessment.org/en/index.html) including regulation (e.g. climate) and cultural (e.g. recreational (Liston-Heyes and Heyes, 1999)). A strong body of previous work documenting peat depth surveys across parts of Dartmoor can be found in (Fyfe et al., 2014, 2010; Fyfe and Woodbridge, 2012; Harrod, 2016; Parry, 2011; Parry et al., 2014; Parry and Charman, 2013), data from some of these surveys were available to this study.

The survey area (Fig. 1b) (406 km^2) consists of moorland overlying the impermeable but locally fractured granite batholith of Dartmoor. All bedrock materials emit radionuclides which can be monitored by airborne gamma-ray spectrometry however, the radiometric signal varies with bedrock type (Rawlins et al., 2007). In order to minimise variability in radiogenesis from the underlying bedrock the survey area was restricted to the granite and microgranite bedrocks, delineated by the 1:50000 bedrock geology map (British Geological Survey, 2016).

2.2. Radiometric dose

Airborne gamma-ray spectrometric data in the energy range 0.40–2.81 megaelectron volts (Beamish et al., 2014) were collected by the NERC Tellus project in summer and autumn 2013. These data were downloaded for use in this research from http://www.tellusgb.ac.uk/Data/airborneGeophysicalSurvey.html. Following Beamish et al. (2014) the air absorbed radiometric dose (D) (nGy·h^{-1}; nanoGray per hour) was calculated using Eq. (1).