Carbon storage in peatlands: A case study on the Isle of Man

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A B S T R A C T

Peatlands contain about one third of the World’s terrestrial carbon (C). Due to their increasing importance in the context of climate change, various studies estimated regional and global carbon stocks. The greatest uncertainty in current C stock estimates is peat depth. Information on peat depth is often lacking or spatially variable, which both limit the accuracy of C stock estimates. We present measurements of peat depth on the Isle of Man and evaluate the C sink of the region. We assess the degree to which estimates of Sphagnum cover can be used to predict peat depth and we identify and quantify various uncertainties in resulting C stock estimates. Total peatland area was identified through classification of aerial photography. Peat depth and Sphagnum cover were measured on a 50 m grid at four study sites in the southern hills on the Isle of Man.

Peatlands at the study sites were generally shallow with low total organic carbon (TOC) contents. Peat depth seemed not to be controlled by local terrain. It is estimated that the C stored per unit area ranges from 14.7 to 22.4 kg C m⁻². The results provided in this study were significantly lower than in other studies, which is likely due to the land use history. The large spatial variability of peat depth resulted in large uncertainty in C stock estimates. Sphagnum proved to be important for the formation of deep peat and could potentially be used to assess the quality of peatlands. Results suggest that peatlands on the Isle of Man will likely act as a C source in the long-term if not maintained and/or restored.

1. Introduction

Peatlands are one of the World’s most important ecosystems covering about 3% of the global land area, with the majority located above 45°N (Madgwick and Parish, 2008; Yu et al., 2011). Peatlands represent a variety of wetlands and are defined as ‘any ecosystem where in excess 0.3–0.4 m of peat has formed’ (Charman, 2002; Harris and Bryant, 2009). Peat is formed in waterlogged and anaerobic conditions that inhibit the complete decomposition of dead plant and animal components (Charman, 2002; Rydin and Jeglum, 2006). Thus, peat largely consists of the partially decomposed remains of plants with an organic matter (OM) content >65%. However, this definition can vary significantly, and the minimum percentage OM required can range from 20% up to 80% (Charman, 2002). Bog peats, dominated by the bog moss Sphagnum, can even reach organic values well over 90% (Gorham, 1995).

Most peatlands started accumulating peat in the early Holocene, around 10,000 years ago, and have continued since then (Strack, 2008; Yu et al., 2011). From special importance for the formation of deep peat are peat mosses – the genus Sphagnum. Sphagnum species are special bryophytes that are adapted to acid, waterlogged and nutrient-poor conditions. Moreover, they create such environments themselves. Sphagnum species have the capacity to store up to 15 to 20 times their dry mass of water between their leaves, which results in a continuously high water table and anoxic conditions. These characteristics and their slow decomposition rate make Sphagnum species extremely important for peatlands (Charman, 2002; Rydin and Jeglum, 2006). They are the main peat formers and without them peatlands would not be as widely distributed (Rydin and Jeglum, 2006). Thus, an extensive cover of Sphagnum is an indicator for high quality peatlands, whereas little Sphagnum and large dry areas with hard peat are typically associated with poor quality peatlands (Cross in press, cited in Charman, 2002).

For millennia peat was mainly regarded as a resource that can be exploited, for fuel, horticulture or forestry, which led to major alterations in peatland hydrolgy and vegetation (Chapman et al., 2003; Charman, 2002). As a consequence, peat accumulation in Europe stopped in over 50% of former mire areas, which makes Europe the continent with the largest peatland losses (Joosten and Clarke, 2002). Peatlands represent about one third of the World’s terrestrial carbon (C) pool, storing 400–500 Gt C and are the most efficient C store of all terrestrial ecosystems (European Environment Agency, 2010; Roulet, 2000). As a result, peatlands are an important long-term sink of atmospheric CO₂ and they could be a cost-effective measure in mitigating and adapting to climate change (Gorham, 1991; Lunt et al., 2010;
Peat accumulation ensures that these regions remain a sink of atmospheric CO$_2$ and thus impact national C sinks and source inventories (Roulet, 2000). As a consequence, peatland restoration has become increasingly important and numerous peatlands across the UK, including projects at Exmoor peatlands, the RSPB Forsinard Flows nature reserve or the Portmoak Moss Woodland Trust Scotland, have been restored (IUCN UK Committee, 2012). The most widespread restoration method is drain blocking, which aims to restore the water table and hydrological regime to a previous state (Holden et al., 2007). To assess the success of restoration measures and to consider peatlands as a climate change mitigation measure it is essential to provide accurate C stock estimates of peatlands as a baseline against which to measure future changes (Garnett et al., 2001; Rogiers et al., 2008). In particular, knowledge of C storage at regional scales (100 to 10,000 km$^2$) is crucial as management and restoration measures at these scales are directly affecting C fluxes (Buffam et al., 2010).

Table 1 presents estimates of C stocks ($\pm$ uncertainties) in peatlands published over the last decade (e.g. Beilman et al., 2008; Buffam et al., 2010; Chapman et al., 2009; Jaenicke et al., 2008; Zauft et al., 2010). However, information on peatland C stocks is still relatively scarce (Zauft et al., 2010) due to uncertainties in peat depth and peat area as well as bulk density (BD) and C content, with peat depth contributing most to the uncertainty (Beilman et al., 2008; Buffam et al., 2010; Garnett et al., 2001; Gorham, 1991). Information on peat depth is often lacking or spatially variable, which both limit the accuracy of C stock estimates (Beilman et al., 2008; Buffam et al., 2010; Wellock et al., 2011).

This study presents estimates of peat depth and C stocks in peatlands on the Isle of Man and we identify the key uncertainties in the resulting C stock estimates. Additionally, we assess the value of remotely sensed data to quantify the peatland area and the importance of Sphagnum and topography as predictors for peat depth. This work is of importance for quantifying uncertainties in C stock estimates in other peatlands, over wider areas. Considering these uncertainties should be a central part of informing management strategies for peatland preservation and restoration aimed at maintaining C storage.

2. Materials and methods

2.1. Site description

Measurements were undertaken at four different sites (A–D) in the southern hills on the Isle of Man, which lies in the Irish Sea between Ireland and England (Fig. 1). The Isle of Man is 51 km long and 21 km wide at its widest point and covers an area of roughly 500 km$^2$ (Robinson and McC Carroll, 1990, cited in Sayle et al., 1995). The sites were chosen in order to cover the major peatland types found on the Isle of Man, such as wet dwarf shrub heath, dry dwarf shrub heath and flush and spring, which account for 85.22, 4.68 and 6.87%, respectively, of the total habitats found on peat on the Isle of Man (Sayle et al., 1995). Sayle et al. (1995) defined heathland as areas occurring on peat <0.5 m on well drained acid soils. Mires, on the other hand, are typically found on peat >0.5 m, while flush and springs are minerotrophic mires associated with a water movement (Rydin and Jeglum, 2006; Sayle et al., 1995). Peatlands at all study sites, particularly dry dwarf shrub heath, are managed through repeated burning and low density grazing. Further, they have been drained extensively and used for peat extraction in the past (Harris et al., 2001; Tomlinson and...
Information on the distribution and area of the different peatland types was taken from Sayle et al.’s (1995) ecological habitat survey. Due to the surrounding sea and the influence of the Gulf Stream, the climate on the Isle of Man is typical ‘Atlantic’ with a mean annual rainfall of 886 mm and relatively mild winters and cool summers. Precipitation generally increases with altitude, as does the frequency of frost, cloud cover and humidity. The Island’s relief is dominated by a central mass of hills with flatter areas in the north and south. The hills are predominantly composed of Cambrian Manx slate, which is the main rock type on which pedogenesis occurs. As a result of the siliceous and base deficient slate, as well as the cool and humid climate, the upland soils on the Isle of Man are predominantly acid (Fullen et al., 2006; Sayle et al., 1995). The main soil types that have developed under these conditions are peaty soils (7–40 cm of peat), podzols, and depending on seasonal surface waterlogging, stagnopodzols (Fullen et al., 1999). Peat formation on the Isle of Man dates back to the latter half of the Holocene when Neolithic cultures cleared most of the forests. This resulted in soil acidification and nutrient depletion, which together with the deteriorating Holocene climate encouraged the formation of peat (Fullen et al., 1996; Fullen et al., 2006). Today, peatlands on the Isle of Man cover just under 12% of the Island’s total area.

2.2. Peatland area

Peatland area can be identified and mapped with remotely sensed data. To identify the peatland area on the Isle of Man, a multispectral image classification was carried out using the ENVI Image Analysis Software (v4.6.1., Exelis Visual Information Solutions Inc., VA, USA). The Image Analysis was based on an aerial photograph of the Isle of Man from 2009 with a 0.2 m resolution (Department of Infrastructure, 2011). A two-pass unsupervised/supervised classification was performed with the Regions of Interest (ROI), needed to ‘train’ the supervised classification, determined through the visual examination of the aerial photograph with the support of ground truth data collected from 10 sites. The supervised classification was run with the maximum likelihood algorithm with a probability threshold of 0.8 for the classification. An accuracy assessment with independent ground truth ROIs was carried out to assess the quality of the classification.

2.3. Peat depth

Peat depth was measured at 472 locations, over three different peat types with a 0.01 m diameter earth rod of 1.2 m length, to depth of contact with mineral surface. For peat depth exceeding 1.2 m the maximum measured value was used. A 0.7 m soil auger and a bulk density (BD) ring (56.55 cm³) were applied to take soil samples for the total C (TOC) content and the BD analysis in the laboratory. Soil samples for the TOC content analysis were taken randomly to a maximum depth of 0.7 m. BD samples were collected at the soil surface. As peat depth on the Isle of Man often varies from 0.1 to 1 m or more on a relatively small scale (<1 m), the peat depth samples were placed systematically on a regular grid at roughly 50 m intervals throughout the sample locations. GPS readings (accurate to approximately 3 m) were made at every individual sample location.

2.4. Sphagnum cover

Based on the fact that an extensive cover of Sphagnum is usually an indicator for high quality sites and that a surface layer of Sphagnum (>10%) is most important for carbon sequestration, it was hypothesized that Sphagnum cover is positively related to the quality of the peatlands (Cross in press, cited in Charman, 2002; Lunt et al., 2010; Hill et al., 2005). Sphagnum cover was estimated using conventional frame quadrats (1 × 1 m). The quadrats were placed systematically where peat depth measures were taken. However, cover estimates risk being subjective, imprecise and biased (Hill et al., 2005; Kercher et al., 2003). Thus, each quadrat was also photographed using a Nikon D3100 with an 18–55 mm lens. Following Luscier et al.’s (2006) methods, the digital images were taken vertically from above at a height of 1.50 m. The images were later imported into ENVI as JPEG files in order to estimate the cover more objectively through a digital image classification (Hill et al., 2005; Luscier et al., 2006). Both unsupervised and supervised classifications were tested in order to analyse the Sphagnum cover. The average between the measured (quadrat) and estimated (photographic) Sphagnum cover was plotted against peat depth and as both variables were not normally distributed a Spearman’s rank correlation test was carried out using SPSS (v14, IBM Corp, NY, USA) to test the relationship between Sphagnum and peat depth. Within each study site the point estimates of peat depth and the average Sphagnum cover were interpolated to a continuous map with an output cell size of 20 m by nearest neighbour resampling using ArcGIS (v 9.2, Esri, NY, USA).

2.5. Topography

Based on previous studies (e.g. Beilman et al., 2008; Chapman et al., 2009; Graniero and Price, 1999) information about topographic factors can improve C stock estimates as they influence the hydrological effects. Slope generally affects the rate of a downslope movement, where shallower peat is expected at steeper slopes and higher elevations (Beilman et al., 2008; Esri Mapping Centre, 2010). Profile curvature and plan curvature, the second derivatives of a surface, have an influence on the acceleration or deceleration of the flow and the convergence and divergence of the flow, respectively (Burrough and McDonnell, 1998; Esri Mapping Centre, 2010; Graniero and Price, 1999). A positive value for profile curvature and a negative plan curvature should favour the formation of peat. This generally leads to a divergence and deceleration of the flow at the bottom of a concave slope resulting in a rising water table (Graniero and Price, 1999).

For this reason, this study carried out a number of correlation tests to determine the relationship between peat depth and elevation, slope, plan curvature and profile curvature. Slope and curvature data were derived from a 20 m grid size DEM using the ‘spatial analysis’ tool within ArcGIS (DEFA, 2011). To evaluate the relationship between peat depth and topographic factors correlation tests between the raster layers were carried out in ArcGIS using the ‘band collection statistics’ tool. The ‘extract by mask’ function within the spatial analyst was applied to adjust the slope, curvature and elevation data to the size of the study area. This resulted in raster layers with the same spatial extent and the same spatial resolution (20 m).

2.6. Laboratory analysis

To measure BD the soil samples were weighed wet then left to dry at 40 °C for a week. The dry samples were then reweighed, and BD was calculated as dry weight/volume (UCL Department of Geography, 2011). A rough estimate of the TOC content is the OM content (Schumacher, 2002). This was analysed via ‘loss on ignition’ (LOI). From each soil sample burning 2 g was placed in a crucible and weighed, then oven dried at 105 °C overnight. The dried samples were re-weighed and put in the furnace at 550 °C for 2 h. Samples were then re-weighed and the mass of soil loss expressed on a dry weight basis was determined by the following equation (Konare et al., 2010; UCL Department of Geography, 2011).

\[
\text{LOI (g/kg)} = \frac{\text{Weight}_{\text{dry}} - \text{Weight}_{\text{ignition}}}{\text{Weight}_{\text{dry}}} \times 1000
\]
C stocks were calculated for each of the four study sites. The area of each site was determined from the map data. The carbon pools (C) for each site were calculated using Eq. (2).

\[ C = A \cdot BD \cdot TOC \cdot D \]  
(2)

In addition, the carbon density (μC) was calculated for each sample point at the study sites via Eq. (3).

\[ \mu C = \frac{BD \cdot TOC \cdot D}{m^2} \]  
(3)

The uncertainty of the C stock estimate (dC) was determined using the standard deviations (SD) of bulk density (dBD), carbon content (dTOC) and peat depth (dD) and combined via Eq. (4) (Chapman et al., 2009):

\[ dC/C = \sqrt{(dBD/BD)^2 + (dTOC/TOC)^2 + (dD/D)^2} \]  
(4)

where A is the peatland area, S the sample point and, BD, TOC and D the mean values for bulk density, total organic carbon and peat depth. Additionally, the average peat depth for each peatland type covered in this study was used to calculate C stocks for the various peatland types. The C density for each peatland type was calculated using Eq. (3) with the average peat depth of each peatland type. The area estimates for dry dwarf shrub heath, wet dwarf shrub heath and flush and spring were derived from Sayle et al.’s (1995) habitat survey.

3. Results

3.1. Peatland area

The supervised classification of peatland areas provided results which could be used for the estimation of the peatland distribution. The main peatland type which could be identified on the aerial photograph was dry dwarf shrub heath, as its brown colour in combination with burning marks was relatively easy to detect. This habitat is also the most extensive peatland type on the Isle of Man (Sayle et al., 1995). Mire and wet dwarf shrub heath, which are mainly covered by cotton-grass (Eriophorum spp.) and/or Sphagnum, were difficult to distinguish from other classes, such as agricultural land or grassland (Sayle et al., 1995). The ROI separability index indicated that the spectral differences between peatland and other land cover classes, including agricultural land, urban areas and coastal areas, were insufficient to separate them. In particular, urban areas and coastal areas, such as beaches had low separability values (~1.7). Image classification resulted in a total peatland area estimate of 52 km². Accuracy assessment revealed that peatland area was generally underestimated, with higher errors of omission (areas of peat misclassified as something else) at 30.83%, than commission (areas of other cover types wrongly misclassified as peat) at 0.41%. This means that peatland was generally correctly classified (user accuracy: 99.59%), but some peatland was possibly overlooked (producer accuracy: 69.17%).

3.2. Peat depth

Over the four study sites peat depth variability within sites was generally higher than among sites (Fig. 4). Site depths typically ranged from 0.02 to > 1.20 m. With a mode of 0.1 m, peat depth at Lanagore (A) and South Barrule (C) was relatively shallow throughout. Similarly, Cross Vein (B) had mostly thin peat, where peat depth was typically 0.15 m. The deepest average peat depth occurred at Glen Rushen Farm (D) (0.48 m). Small areas of deeper peat were found at all sites. However, such areas were usually less common and higher values were primarily outliers (Fig. 4). Just under 2% of the measurements were deeper than 1.20 m. Peat depth variability around the mean was fairly large at all locations, with standard deviations ranging from 0.11 m at South Barrule to 0.28 m at Glen Rushen Farm. Peat depth was skewed towards shallow depths at all sites (median < mean, Fig. 4).

3.3. Sphagnum cover

Fig. 4 illustrates the average between the measured and the estimated Sphagnum cover and its variation at the study sites. The total Sphagnum cover ranged from 0 to 86%, whereas the lowest maximum value was recorded at Glen Rushen Farm (D) (66%). Similarly to peat depth the Sphagnum cover was heterogeneous within the sites. Apart from South Barrule (C), where Sphagnum mosses were relatively uncommon, the average Sphagnum cover showed little variation among sites. The standard deviation was extremely large at all sites. The distribution of the data is right-skewed at all sites (median mean). In other words, the deviation is much larger towards higher than lower values.

The mean visual estimate of the Sphagnum cover was 22%, ranging from 0 to 100%. With a standard deviation of 32% the Sphagnum cover showed a large variation around the mean. Images for the digital image classification were only taken where Sphagnum mosses were found. In total 179 images were analysed. Due to the spectral similarity of Sphagnum, grass and heather, unsupervised classification proved to be too inaccurate to identify the Sphagnum cover. Therefore, the quadrat photos were analysed via supervised classification using the maximum likelihood algorithm with a probability threshold of 0.8 and 3 iterations. Surprisingly, the Sphagnum cover that resulted from the supervised classification was significantly lower than the visual estimate, with differences up to 74%. However, the relatively well-represented distribution of Sphagnum cover from the classification suggests that visual estimates were probably an overestimate, while classification tended to underestimate Sphagnum cover. Another problem occurred at quadrats where Sphagnum coexisted with heather, as they were difficult to separate from each other and heather often covered the Sphagnum mosses. In cases where Sphagnum was not visible on the photograph the missing data was gap filled with the results from the visual estimate. Usually, this was only the case where Sphagnum cover was low. An average between the visual estimate and the supervised classification was built for the further analysis and the Sphagnum maps.

The Spearman’s rank correlation test revealed a positive relationship between Sphagnum cover and peat depth (P < 0.001, r = 0.721), which confirms the hypothesis that Sphagnum cover is a predictor of peat depth. Fig. 2 shows the relationship between peat depth and Sphagnum. It can be seen that peat depth tends to increase with an increasing Sphagnum cover. Due to the high variation a linear trend fits the data only limited, which is reflected in the R² value (0.46).

3.4. Topography

Of the raster correlation tests that were carried out, only one resulted in a significant correlation (r = 0.535). Neither slope nor plan and profile curvature correlated with peat depth at any of the sites. Elevation was negatively correlated to peat depth at Lanagore, but only weakly (r = 0.535). None of the other sites correlated with elevation.
3.5. Spatial distribution of peat depth and Sphagnum

Fig. 3 illustrates the peat depth and Sphagnum cover distribution at the four study sites. Areas of deeper peat and higher Sphagnum cover are clearly visible on the maps. At South Barrule (C) peat mosses and deeper peat were concentrated to a fairly small area, while the other sites (A, B, D) showed a larger distribution of Sphagnum as well as deep peat. Sphagnum mosses were often found on areas of deeper peat or in wet depressions. Generally, extensive dry areas with shallow peat also lack Sphagnum species. An exception to this pattern can be identified at Glen Rushen Farm (D) where Sphagnum was also found on shallow peat.

3.6. BD and TOC

In total 27 soil samples were collected from the four study sites and analysed in the laboratory. A summary of the results is shown in Fig. 4. Sampling was limited either due to site wetness or high density of vegetation. 13 soil samples were taken from site A, 5 from site B, 7 from site C and 2 samples were collected at site D. BD ranged from 0.07 to 0.25 g cm\(^{-3}\) and was on average 0.15 g cm\(^{-3}\). The peat samples had a TOC content of 306 g kg\(^{-1}\) on average. TOC contents ranged from only 84 up to 473 g kg\(^{-1}\). Compared to the BD, the median of TOC contents varied substantially among sites (158–456 g kg\(^{-1}\)), with much higher medians at South Barrule (C) and Glen Rushen Farm (D) than Lanagore (A) and Cross Vein (B) (Fig. 4). There were two outliers in the BD measures as well as in the TOC results. The TOC outliers were only outliers within sites and, therefore, kept for the further analysis. The two high results for the BD (0.35 g cm\(^{-3}\)), however, also exceeded the typical values for BD, and were disregarded. As the sample sizes varied significantly between sites the total average of the laboratory analysis results was used for the C stock calculations.

3.7. C stocks

Mean C stored at the study sites ranged from 1.40 kt at Glen Rushen Farm to 7.51 kt C at Lanagore (Table 2). C storage per unit area ranged from 0.9 to 55.8 kg C m\(^{-2}\). As expected, most C per unit area was stored at Glen Rushen Farm (22.4 kg C m\(^{-2}\)), followed by Lanagore (14.7 kg C m\(^{-2}\)). The standard deviation was large, ranging from 5.4 to 13.2 kg C m\(^{-2}\) (Table 3). The largest contribution to uncertainty in C stocks arose from peat depth, followed by the TOC content. This uncertainty was reduced by 10–20% by taking all peat depth data into account.

Fig. 2. Relationship between Sphagnum cover and peat depth.

Fig. 3. Sphagnum cover and peat depth maps, a) Lanagore, b) Cross Vein, c) South Barrule, d) Glen Rushen Farm.
As Table 4 shows, dry dwarf shrub heath, which accounts for the majority of peatland on the Isle of Man, stores 699.00 kt of carbon on average with an uncertainty of ±694.50 kt C. Flush and spring, only covering 4.5 km², contains 109.00 kt C (±86.30) and wet dwarf shrub heath stores on average 62.00 kt C (±44.80). Due to the deeper peat (0.53 ± 0.32 m) of flush and spring the C density of these peatlands is higher compared to dry dwarf shrub heath (Table 4).

4. Discussion

4.1. Classification of peatland and Sphagnum

For the investigation of the peatland distribution on the Isle of Man both unsupervised and supervised classification methods were applied. Only the supervised classification allowed sufficient discrimination of peatland areas. Peatlands, particularly heathland, are relatively easy to detect on medium to high spatial resolution images, such as aerial photographs or Landsat images (Brown et al., 2007; Krankina et al., 2008). A general problem encountered here was the pixel heterogeneity of peatland as well as the similar spectral response of peatland and other land cover classes. The use of above-ground vegetation as a proxy for peatlands is likely to lead to omission of some peatland areas.

4.2. Variability of peat depth and implications for upscaling

Peat depth at the four study sites was spatially heterogeneous, reflected by the large standard deviations of depth measurements in line with the findings of previous studies (e.g. Beilman et al., 2008; Buffam et al., 2010; Wellock et al., 2011). Peat depth measured at the four study sites is well below the global mean of 2.30 m (Gorham, 1991). With a mode of 0.10 to 0.15 m the majority of peatlands in the southern hills are shallow, as a result of the large area of dry dwarf shrub heath. Whether the average peat depth measured in the southern hills is representative for all peatlands on the Isle of Man is questionable. Peatlands in the southern hills differ from peatlands in the northern hills as well as the lowlands. Previous studies have reported significantly deeper peat deposits in the northern hills and in the lowlands.

<table>
<thead>
<tr>
<th>Site</th>
<th>Area [m²]</th>
<th>Sample size</th>
<th>TOC [g kg⁻¹]</th>
<th>Peat depth [m]</th>
<th>BD [g cm⁻³]</th>
<th>Stock [kt C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>511,520</td>
<td>227</td>
<td>306 (± 144)</td>
<td>0.32 (±0.25)</td>
<td>0.15 (±0.03)</td>
<td>7.51 (±7.00)</td>
</tr>
<tr>
<td>B</td>
<td>193,889</td>
<td>83</td>
<td>306 (± 144)</td>
<td>0.29 (±0.23)</td>
<td>0.15 (±0.03)</td>
<td>2.58 (±2.40)</td>
</tr>
<tr>
<td>C</td>
<td>261,919</td>
<td>124</td>
<td>306 (± 144)</td>
<td>0.17 (±0.12)</td>
<td>0.15 (±0.03)</td>
<td>2.04 (±1.80)</td>
</tr>
<tr>
<td>D</td>
<td>63,530</td>
<td>38</td>
<td>306 (± 144)</td>
<td>0.48 (±0.29)</td>
<td>0.15 (±0.03)</td>
<td>1.40 (±1.10)</td>
</tr>
</tbody>
</table>

Table 2 Summary of the C density results at each study site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Median [kg C m⁻²]</th>
<th>Mean [kg C m⁻²]</th>
<th>SD [kg C m⁻²]</th>
<th>Minimum [kg C m⁻²]</th>
<th>Maximum [kg C m⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9.3</td>
<td>14.7</td>
<td>11.8</td>
<td>2.3</td>
<td>55.8</td>
</tr>
<tr>
<td>B</td>
<td>9.3</td>
<td>13.4</td>
<td>10.6</td>
<td>0.9</td>
<td>55.8</td>
</tr>
<tr>
<td>C</td>
<td>7</td>
<td>7.8</td>
<td>5.4</td>
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<td>18.6</td>
<td>22.4</td>
<td>13.2</td>
<td>4.6</td>
<td>55.8</td>
</tr>
</tbody>
</table>
4.3. Relationship between Sphagnum and peat depth

The positive correlation between Sphagnum and peat depth suggests that Sphagnum cover can be used as an indicator for peat depth and the quality of the peatland. However, a linear trend explains the relationship only to a limited degree due to the high variation in the data (Fig. 2). Occasionally, Sphagnum was also found on shallow peat. These locations could possibly be an indicator for growing peatlands due to a rising water table. As seen in Fig. 3 such conditions were typically found at Glen Rushen Farm. Sphagnum at this site has often started growing in old drainage channels that have blocked themselves naturally followed by a rising water table. Areas of deep peat combined with a low Sphagnum cover, on the other hand, have potentially been degraded by past (peat extraction, drainage) and current (repeated burning, low density grazing) land uses. Generally, deep peat was covered by an extensive Sphagnum cover, which was typical for flush and wet heath with a relatively high water table. These areas are currently more likely to absorb carbon. In contrast, shallow peat and low-to-absent Sphagnum cover were often the characteristics of dry dwarf shrub heath, which is typically associated with drainage, rotational burning and grazing. Thus, dry dwarf shrub heath is usually found at the end of a typical spectrum of degradation. The vegetation of this peatland type tends to form thin organic soils with little value for C sequestration without restoration (JNCC, 2011; Lunt et al., 2010). As a consequence, C stocks of dry dwarf shrub heath will possibly decrease in the future. Based on the fact that the majority of peatland on the Isle of Man is dry heath, it seems probable that C stocks on the Isle of Man will decrease rather than increase in the next decades if not restored. A decrease in C stocks may be accelerated by future temperature and precipitation changes (Charman et al., 2008; Firth and Hutchins, 2006; Strack, 2008).

Further information about the C exchange between peatlands and the atmosphere, better monitoring of changing Sphagnum cover and peat depth measurements from the northern hills will be essential for more precise answers on the national C stock development (National Trust). In addition, although it seems necessary to restore peatlands in order to enhance their C storage potential, there is a concern that peatland rewetting potentially leads to increased CH4 and dissolved organic C (DOC) release, which affects the GHG balance and the water quality in terms of colour, taste and aesthetic value (Baird et al., 2005; Holdren, 2005; Worrall et al., 2007). Future research should focus on quantifying and monitoring impacts of restoration measures on the peatland hydrology, the methane emissions as well as the C stocks.

4.4. Importance of topographic factors for the formation of peat

Although topography has a major impact on soil drainage, the results of this study showed only one significant correlation between elevation and peat depth at Lanagore (A), where deeper peat was generally found at lower elevations. This is consistent with other studies, which observed that peat usually accumulated in lower and flatter areas (Beilman et al., 2008; Charman, 2002). No other relationships between topographic factors and peat depth were found at this scale and extent, which suggests that local terrain does not control peat depth and can therefore not be used to predict the distribution of soil carbon. These results may be partly explained by the relatively small study site areas and the small variation in topography. However, similarly Beilman et al. (2008) and Garnett et al. (2001) found no significant relationship between peat depth and elevation or slope and peat depth.

4.5. C stocks and uncertainties

The C storage per unit area (14.7–22.4 kg C m\(^{-2}\)) found here is relatively low. Chapman et al. (2009) estimated values between 15.0 and 400.0 kg C m\(^{-2}\) in Scottish peatlands; Buffam et al. (2010) showed regional mean C stocks of 104.0 ± 19.0 kg C m\(^{-2}\) in the Northern Highlands Lake District, United States. Similarly, the values calculated by Zauft et al. (2010) for German peatlands and Beilman et al. (2008) for Canadian peatlands resulted in significantly larger C stocks (54.8–206.8 kg C m\(^{-2}\) and 53.0–165.0 kg C m\(^{-2}\), respectively). The differences can partly be explained by the relatively shallow peat depth found on the Isle of Man, and the low TOC contents, likely due to the land use history, including peat extraction, drainage, managed burning and low density grazing, of the peatlands covered in this study (Harris et al., 2001; Tomlinson and Charter, 2006). The majority of previous studies calculated C stocks with mean peat depth values of approximately 2 m and TOC contents of 52% (Buffam et al., 2010; Chapman et al., 2009; Clymo et al., 1998; Gorham, 1991). The TOC contents of this study, which are 306 g kg\(^{-1}\) (30.6%) on average, are comparable to Zauft et al.’s (2010) results for topsoils of degraded peatlands in Germany (22%–41%) and the C stocks are similar to Wellock et al.’s (2011) measured C stocks of afforested peatlands in Ireland (18 kg C m\(^{-2}\) with a peat depth of 0.48 m). Surprisingly, the median of TOC ranged substantially (158–456 g kg\(^{-1}\)) among the study sites as well as within the study sites (Fig. 4). The median of TOC at South Barrule (C), where peat was shallow throughout and the TOC content expected to be lowest, was highest. This may be due to the presence of large organic particles (twigs or roots) in the soil samples, which directly affect the results of the TOC content (Schumacher, 2002). Due to the spatial variability of peat depth and TOC the resulting C stock estimates contained a large degree of uncertainty. Another area of uncertainty is variation of C stocks at different depths, which was not investigated in this study due to time restrictions. Generally, the uncertainties given here are significantly higher than those of previous studies (Table 1). This is mainly due to the smaller SD of each parameter calculated by other studies. Maximum % peat depth uncertainty in Jaenicke et al.’s (2008) study ranged from 13% to 25%. Chapman et al. (2009) calculated % uncertainties (SD/mean) for bulk density, peat depth, area and C, which resulted in 8.3, 7.2, 4.5 and 3.4 respectively. In contrast to this and Buffam et al.’s (2010) study, they concluded that incorporating better peat depth data reduced the total uncertainty from approximately 50% to 4.3%.

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Table 4

<table>
<thead>
<tr>
<th>Peatland type</th>
<th>Area (^{1}) ([\text{km}^{2}])</th>
<th>TOC [g kg(^{-1})]</th>
<th>Peat depth [m]</th>
<th>BD [g cm(^{-1})]</th>
<th>C density [kg C m(^{-2})]</th>
<th>Stock ([\text{kt C}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry dwarf shrub heath</td>
<td>56.4</td>
<td>0.27</td>
<td>0.15</td>
<td>12.4</td>
<td>699.00</td>
<td></td>
</tr>
<tr>
<td>Wet dwarf shrub heath</td>
<td>3.0</td>
<td>0.45</td>
<td>0.15</td>
<td>20.6</td>
<td>62.00</td>
<td></td>
</tr>
<tr>
<td>Flush and spring</td>
<td>4.5</td>
<td>0.53</td>
<td>0.15</td>
<td>24.3</td>
<td>109.00</td>
<td></td>
</tr>
</tbody>
</table>

\(^{1}\) Area estimates were derived from Sayle et al.’s (1995) Habitat Survey.

Upscaling the average peat depth from the southern hills to the entire Island is therefore problematic and accurate measurements of peat depth in the northern hills will be required to estimate national C stocks.
5. Conclusion

This study provides most consistent baseline estimates of C stocks for the southern peatlands on the Isle of Man (14.7–22.4 kg C m⁻²). Peat depth was spatially more variable and TOC contents were significantly lower than in other studies, which is likely due to the historicalpeat extraction, drainage) and current (repeated burning, low density grazing) land uses. The spatial variability of peat depth and TOC were the key determinants of the uncertainties on the resulting C stock estimates, which prove the importance of incorporating accurate peat depth data when calculating C stocks. Another key uncertainty of this study is the variation of C stocks with peat depth and future research needs to focus on further soil sampling, including not only more soil samples per peatland type, but also from different depth increments. Further, we show that remote sensing is a valuable tool to derive aerial estimates of peatlands, particularly heathland, albeit potentially underestimating the peatland area. Although C stocks of the southwestern peatlands on the Isle of Man are relatively low, they are a significant source of vulnerable C if not restored, considering they only account for approximately 2% of the total peatland area on the Isle of Man, in particular, when comparing them to the Isle of Man’s reported emissions (2008: 7000 kt of CO₂ equivalent) (Billett et al., 2011; McEvoy Pers. Comm.).

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References


