Spatial variation in bulk density and soil organic carbon in the Bamford water treatment works catchment

Funded by: Coldhouse Collective; Peak District National Park Foundation; National Grid; & CLIF

Prepared by:

Moors for the Future Partnership

2021

Prepared by

Moors for the Future Partnership
The Moorland Centre, Edale, Hope Valley, Derbyshire, S33 7ZA, UK

T: 01629 816 339
M: 07972 734 077
E: @peakdistrict.gov.uk
W: www.moorsforthefuture.org.uk

Suggested citation: Crouch, T and Chandler, D. (2021) *Spatial variation in bulk density and soil organic carbon in the Bamford water treatment works catchment*. Moors for the Future Report, Edale.

Contents

List of Figures

List of Tables

1. Summary

This study investigated how much carbon is stored within the blanket peat in the Bamford Water Treatment Works catchment in Derbyshire, UK. It builds upon the findings and recommendations of a 2011 peat depth survey of the same catchment, using a series of full profile peat cores to perform soil bulk density and carbon analysis, from which the amount of carbon stored in the catchment was estimated.

The study found that the soil bulk density and carbon concentration of peat within the Bamford catchment follows a similar pattern: high in the uppermost layer of the bog, lower in the main peat body, and higher at the base of the bog. The high bulk density near the surface suggests that the acrotelm has been lost, resulting in a haplotelmic bog, consisting only of catotelm. There is a strong positive linear relationship between bulk density and carbon concentration, which demonstrates the importance of accurate soil bulk density values when estimating the carbon stored within peatlands. It is estimated that approximately 9,000,000 t C is stored within the peat soils of the Bamford WTW catchment, which equates to approximately 1000 t C ha^{-1}.

2. Introduction

Peat is a soil characterised by its relatively high organic matter content, which may range from 30% to almost 100% (Lindsay, 2010). Peat is formed from carbon rich, dead and decaying plant material, which has accumulated in waterlogged conditions over thousands of years (IUCN, 2021a; Natural England, 2010). Peat has a very low mineral content; therefore, it is much less dense than other soil materials, and most of its volume is occupied by water when wet. Soils with peat layers generally have dry bulk densities ranging from 0.06 g cm^{-3} to 0.4 g cm^{-3} depending on the level of humification, compaction or mineral content (JNCC, 2011). The typical carbon content of peat is approximately 52% carbon by dry weight (Lindsay, 2010). Organic matter is different to total organic carbon in that it includes all elements (hydrogen, oxygen, nitrogen, etc.) that are components of organic compounds, not just carbon (Soil Quality, 2021).

Ecosystems with peat deposits are known as peatlands (Ramsar, 1971, cited in JNCC, 2011). Peatlands cover 3% of the world's land area, an estimated 4 million km^2, and are found in 180 countries worldwide, and across all continents (IUCN, 2021a). In the UK, peatlands cover 12% of the total land area, an estimated 30,000 km^2 (Evans et al., 2017). There are three broad peatland types in the UK; blanket bog, raised bog and fen. Blanket bog is the most widespread semi-natural habitat in the UK but globally it is rare. The UK has 13% of the world's blanket bog and that makes it internationally important (IUCN, 2021a). Blanket bogs are found in the north and west of the UK, extending from Devon in the south to Shetland in the north (JNCC, 2011; Natural England 2010).

Blanket bogs develop in cool wet climates where peat has formed a layer across upland landscapes. They are fed only by rainwater (ombrotrophic), which makes them nutrient-poor and acidic. In these conditions when wetland plants die they do not fully decompose, so instead they accumulate, forming peat. Peat forms very slowly, in an undamaged state between 0.5-1 mm of peat can be accumulated annually (Lindsay, 2010). Peat has been forming across the UK uplands for about 5-6,000 years creating a landscape in which the peat depth can vary considerably from a few centimeters to more than 6 m (IUCN, 2021a).

Peatlands in general provide a number of ecosystem services which can be grouped into four broad categories: provisioning (food, fresh water, wood and fibre, fuel); regulating (climate, flood, disease, water), cultural (aesthetic, spiritual, educational, recreational); and supporting services (nutrient cycling, soil formation, primary production) (Millennium Assessment, 2005). Peatlands also provide unique habitats and biodiversity which are recognised under national and international legislation (JNCC, 2011; Natural England 2010).

Peatlands are the world's largest terrestrial store of carbon; estimated to store at least 550 Gigatonnes of carbon globally, which is more than twice the carbon stored in all the world's forests (IUCN, 2021a). In an undamaged state peatlands can accumulate between 0.1 – 0.2 tonnes of carbon per hectare per year (Natural England, 2010); however, only around 20% of UK peatlands are in an undamaged state where they remain waterlogged and actively continue to form peat and therefore sequester carbon (IUCN, 2021a).

In December 2020, the Committee on Climate Change recommended that the UK set a Sixth Carbon Budget (CCC, 2020a). This recommendation requires a reduction in UK greenhouse gas (GHG) emissions of 78% by 2035 relative to 1990 levels and places the UK on the path to achieve Net Zero by 2050 (CCC, 2020a). According to the Committee on Climate Change, the Sixth Carbon Budget can be met through four key steps: 1) take up of low-carbon solutions, 2) expansion of low-carbon energy supplies, 3) reducing demand for carbon-intensive activities, and 4) land management and greenhouse gas removal. Step 4 is of particular relevance to the current study as it includes the recommendation that 'peatlands are widely restored and managed sustainably' (CCC, 2020b). Specific targets relating to step 4 include an increase in the area of restored peatland from 25% currently to 58% in 2035 and 79% by 2050, and the restoration of all upland peat by 2045 (or stabilised if degradation is too severe to restore to halt carbon losses) (CCC, 2020b).

Of the 30,000 km^2 of UK peatlands, approximately 6,400 km^2 (22%) is estimated to remain in a near-natural condition. This area of near natural peat is believed to act as a significant net sink for CO_2 (~1,800 kt CO_2 yr^{-1}) (Evans et al., 2017). This CO_2 sink is counterbalanced by similar emissions of methane (CH_4) making near-natural peatlands close to carbon neutral (Evans et al., 2017). However, the remaining 78% of UK peatlands have been modified in some way, and in total the UK's peatlands are estimated to be emitting approximately 23,100 kt

$CO_2e\ yr^{-1}$ of GHG emissions (Evans et al., 2017). In January 2021, peatlands were formally included in the UK GHG emissions inventory adding 3.5% to national emissions (IUCN, 2021b).

According to Lindsay (2010), the carbon store could be described as the bottom line for peatlands and the carbon debate. Peatlands store enormous quantities of carbon, which in Britain have been slowly accumulating for thousands of years. The important question today is just how much carbon continues to be held in the UK's peatlands (Lindsay, 2010).

The current study investigated how much carbon is stored within the blanket peat in the Bamford Water Treatment Works (WTW) catchment in Derbyshire, UK. This study builds upon the findings and recommendations of the 2011 peat depth survey of the Bamford WTW catchment (Crouch et al., 2011), using a series of full profile peat cores to perform soil bulk density and carbon analysis, from which the amount of carbon stored in the catchment is estimated.

3. Aims and objectives

The overall aim of this study was to calculate the soil carbon stock of the blanket peat soils within the Bamford WTW catchment. To do this data were required on soil bulk density and carbon content. Spatial variation in soil bulk density and carbon content, both with depth and between the sub-catchments within the Bamford WTW catchment, were also investigated.

4. Study site

The Bamford WTW catchment, comprised of 11 separate sub-catchments, is located in north Derbyshire, within the Peak District National Park, southern Pennines, UK (Figure 4-1). The catchment is 20,159 ha in area; peat soils cover 12,677 ha (63 %), of which deep peat soils (blanket peat and seasonally wet deep peat to loam) represent 6,700 ha (33 %) and shallow peat (peat to loam over sandstone and shallow peat over sandstone) represent 5,977 ha (30

%) (based on The National Soil Resources Institute (NSRI) geographic database (accessible through LandIS[1])).

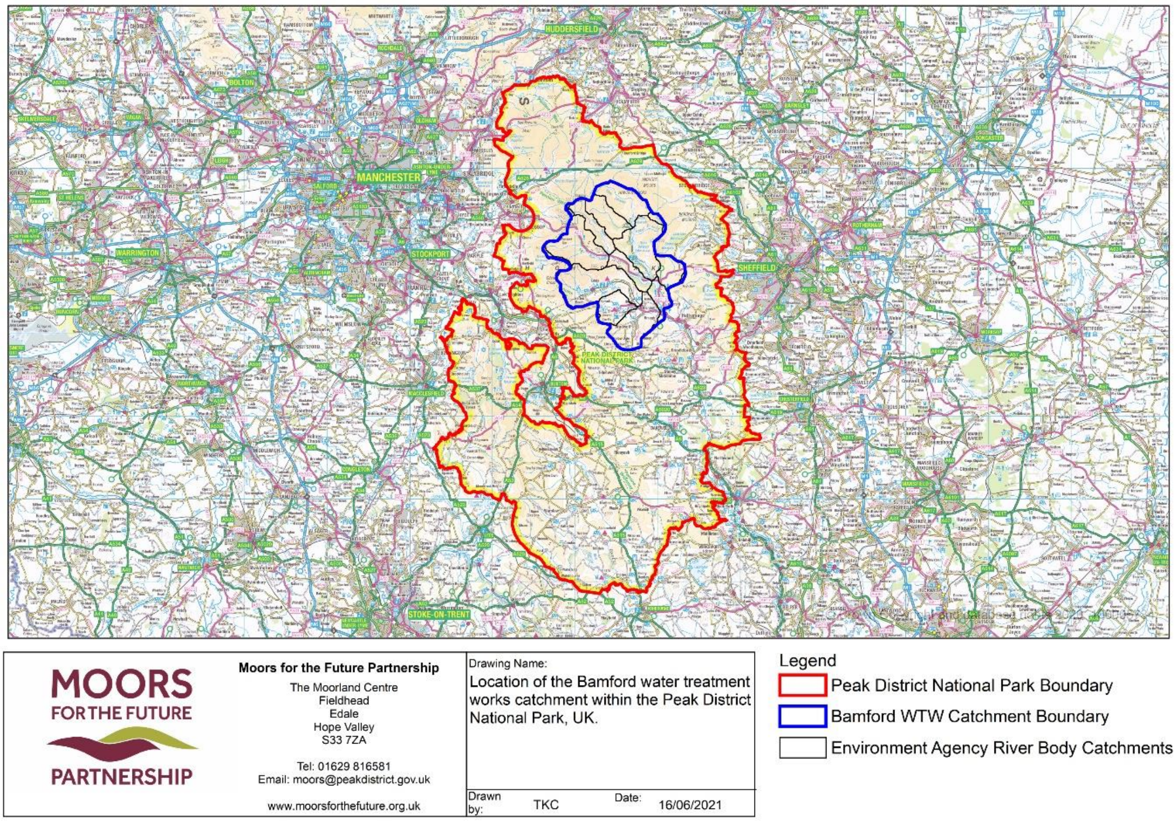

Figure 4-1: Location of the Bamford water treatment works catchment within the Peak District National Park, UK

5. Methodology

In order to calculate how much carbon is held in the peatlands of the Bamford catchment, accurate figures were required for the extent and depth of the peatland, and the soil bulk density and carbon content contained within the peat. The extent of the peatland is based on the National Soil Resources Institute geographic database (accessible through LandIS[2]). The peat depth is based on data collected by Moors for the Future Partnership (MFFP) in 2011 (Crouch et al., 2011). The data collected within the current project will provide the information required on soil bulk density (BD) (in g cm^{-3}) and soil carbon (C) content (in %).

[1] LandIS is the 'Land Information System', a substantial environmental information system operated by Cranfield University, UK. http://www.landis.org.uk

[2] LandIS is the 'Land Information System', a substantial environmental information system operated by Cranfield University, UK. http://www.landis.org.uk

Soil bulk density is the amount of soil per unit volume. It is one of the most useful parameters of soil physical structure, and influences soil porosity, macro- and micropore volume, and soil biodiversity. Bulk Density determinations are also necessary in converting soil carbon content (in %) into a carbon concentration or stock (in g cm^{-3}) (Emmett et al., 2008).

5.1. Survey design

In 2011, MFFP carried out a peat depth survey across the deep peat soils within the Bamford WTW catchment. The deep peat soils, together with a surrounding 20 m buffer, constituted the survey area, which measured 82.67 km^2. In this survey, peat depth was measured at 400m intervals within a triangular grid configuration (see Crouch et al., 2011 for further details). This is consistent with the PAA (2012) guidelines of between 250-500m intervals for very large sites (i.e. tens of km^2 to several hundred km^2).

The current survey was aligned with the previous peat depth survey. However, as soil bulk density and carbon content is likely to be less variable than peat depth (Chapman et al., 2015), and more time consuming and costly to collect and analyse, fewer peat cores than peat depth points were retrieved. Initially, a ratio of 1:6 for bulk density to depth sampling (Smith et al., 2009, cited in Chapman et al., 2015) was proposed which resulted in 85 cores. This was too many to cover within the budget and timeframe of the project; therefore the locations were reduced by removing any locations with a measured peat depth of less than 50cm, leaving 67 locations.

5.2. Field methodology

A box corer (see Figure 5-1) was used to retrieve intact, uncompressed peat cores from the surface to a depth of up to 50 cm. The box corer has a sharp cutting edge, which with the aid of a serrated knife, was designed to cut through vegetation with minimal compaction of the peat. Below this, a Russian corer (see Figure 5-2) was used to retrieve cores from 30 cm to the full peat depth. The Russian corer consists of a 50 cm long semi-cylindrical sample chamber with a rotating fin attached to the face of the chamber and a 10 cm long solid conical nose section (ARCA, 2014). Due to disturbance caused by the conical nose section of the corer, standard procedure when sampling a full peat profile is to form two parallel boreholes within 30 cm of each other (ARCA, 2014) (see Table 5-1).

Figure 5-1: Using a box corer to retrieve a peat core from the surface to a depth of 50 cm (image by John Moore, University of Manchester)

Figure 5-2: Using a Russian corer to retrieve a peat core from 30 cm to full peat depth (image by John Moore, University of Manchester)

Table 5-1: Coring strategy

Borehole 1 – Box Corer	Borehole 2 – Russian Corer	Borehole 3 – Russian Corer
0-50 cm	30-80 cm	80-130 cm
	130-180 cm	180-230 cm
	230-280 cm	280-330 cm
	330-380 cm	

A number of box corers were available; therefore these samples were wrapped in cling film and transported from the field site to the MFFP laboratory in the box corer, where they were divided into the required depth samples (i.e. 0-15 and 15-30 cm). During transportation from field to laboratory, the samples were kept horizontal to avoid compression, which would have affected the soil bulk density calculations. As the Russian core samples were not to be further divided, i.e. each 50 cm section of core formed one sample, these cores were put directly into plastic zip lock bags at the field site.

5.3. Lab methodology

The samples were sent to a commercial laboratory for the calculation of soil bulk density (in g cm^{-3}) and total carbon content (in %).

For soil bulk density analysis (reference method ISO 11272), samples were dried in a fan assisted oven at 105°C until a constant weight was achieved and then weighed with a 2 decimal balance. The samples were then sieved through a 2 mm sieve to retrieve the above 2 mm fraction (stones) which were weighed (François Bochereau, personal communication, 14 April 2021).

For total carbon analysis (reference method ISO 10694 and 13878), a combustion method using a Carlo Erba CN analyser (Flash1112 series) was used. Samples were ball milled for homogenisation at milligram level. Around 7 mg of milled peat were weighed in tin capsules using a 6 decimal balance and then pressed before being analysed for total carbon. As the samples were acidic (pH <7), it is assumed that there were no carbonates present; therefore total carbon equals organic carbon (François Bochereau, personal communication, 14 April 2021).

5.4. Statistical analysis

5.4.1. Outliers

Outliers were identified in SPSS by creating boxplots. The boxplots (see Figure 10-1-Figure 10-3 in Appendices) show outlier values (marked by small circles) and extreme values (marked by stars). Outliers were defined as values which fell outside of 1.5 times the interquartile range.

Twenty outliers were identified in the soil density dataset (10.1 Appendix A). The majority of these outliers were associated with samples being composed of clay, or shallow peat overlaying clay. These outlying data points were not included in the calculation of soil bulk density of deep peat, and were analysed separately.

Seven outliers were identified in the soil carbon concentration (g cm^{-3}) dataset (10.3 Appendix C). Once the samples with outlying soil density values were removed this was reduced to 3 outliers (2 outliers and 1 extreme); however the mean (0.713 g cm^{-3}) and 5% trimmed mean (0.711 g cm^{-3}) were very similar so these outliers were not removed.

5.4.2. Calculations

5.4.2.1. Carbon concentration

Equation 1 was used to calculate carbon concentration (g cm^{-3}) (Emmett et al., 2008):

Equation 1: Carbon concentration

Carbon concentration (g cm^{-3}) = bulk density (g cm^{-3}) x carbon content (%) / 100

5.4.2.2. Carbon stock within the Bamford WTW catchment

Equation 2 was used to calculate the carbon stock of the entire Bamford WTW catchment:

Equation 2: Carbon stock

Carbon stock (g) = area (cm^2) x bulk density (g cm^{-3}) x carbon content (%/100) x depth cm

Carbon stock (g) was then converted to carbon (mt) by dividing by 1,000,000.

The values for mean bulk density and carbon content were obtained from the current study. The value for mean peat depth was obtained from the 2011 peat depth survey (Crouch et al., 2011).

Carbon stock was also calculated for each depth category, using Equation 2 but with the addition of the following steps:

1. The number and percentage of peat depth measurements (from the 2011 peat depth survey) within each depth category was calculated.
2. The area within each peat depth category was calculated (total area cm^2 x percentage of measurements within depth category).
3. For depth, the mean length of sample was calculated from the current study for each depth category.

5.4.3. Statistical analysis

Where the assumptions of normality and equal variance were met, a one-way ANOVA was used to compare the effect of depth / site on soil bulk density and carbon concentration, and post hoc comparisons were made using Tukey HSD tests. Where these assumptions were not met an Independent-Samples Kruskal-Wallis Test was used.

6. Results

6.1. Soil bulk density

6.1.1. Spatial variation in soil bulk density with depth

The mean soil bulk density (g cm^{-3}) at 0-15 cm depth was 0.143 g cm^{-3}. It then dropped to 0.108 g cm^{-3} at 15-30 cm depth, remained steady at between 0.121 and 0.127 g cm^{-3} at 30-230 cm depth, before increasing again to around 0.149 g cm^{-3} at 230-380 cm depth (see Figure 6-1, Figure 6-2 and Table 6-1).

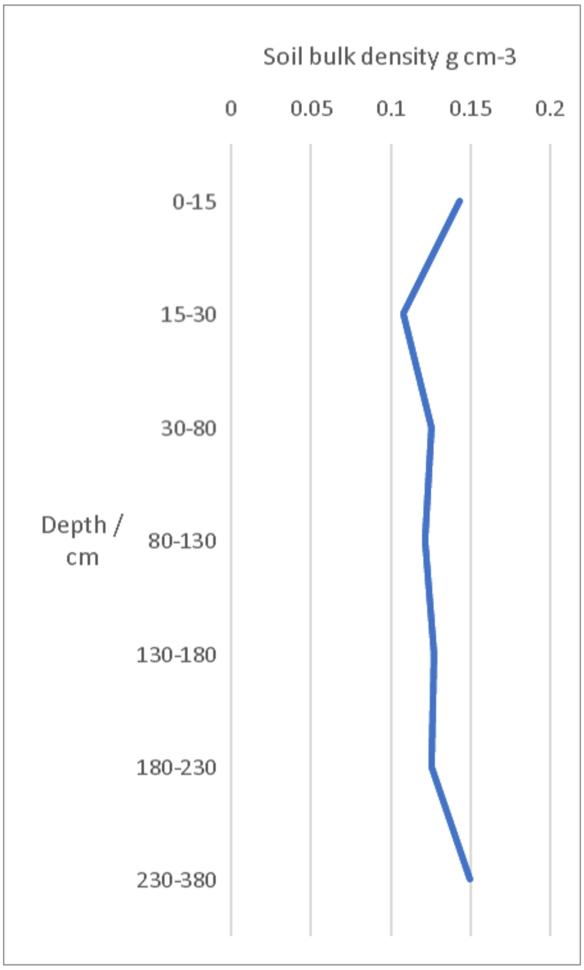

Figure 6-1: Mean soil bulk density (g cm-3) with depth

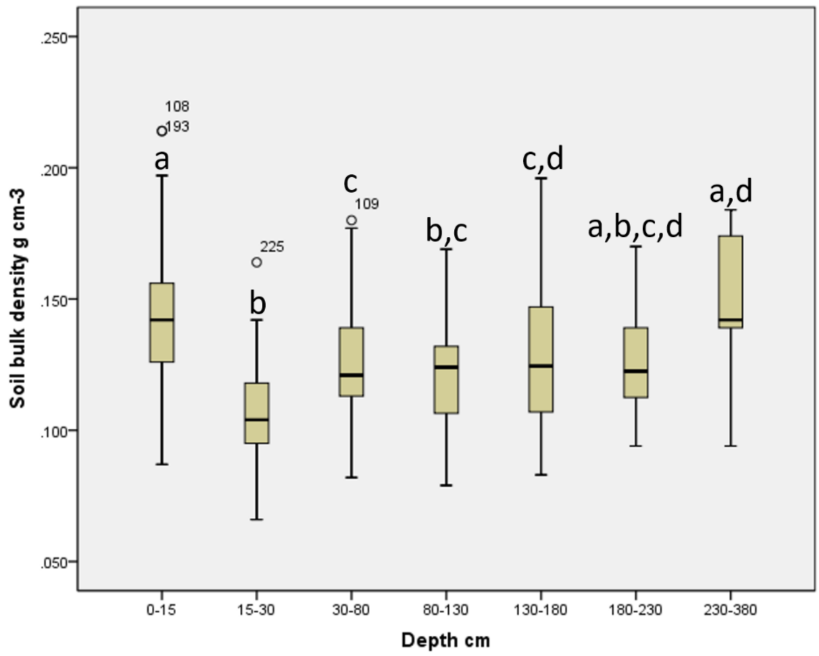

Figure 6-2: Boxplot showing soil bulk density with depth. Outliers are indicated with circles and values, categories which share a letter are not significantly different (p<0.05).

Table 6-1: Summary statistics for soil bulk density (g cm-3)

Depth / cm	N	Min	Mean	Median	Max	Standard deviation	Standard error
0-15	62	0.087	0.143	0.142	0.214	0.028	0.004
15-30	57	0.066	0.108	0.104	0.164	0.019	0.003
30-80	58	0.082	0.126	0.121	0.180	0.022	0.003
80-130	47	0.079	0.121	0.124	0.169	0.211	0.003
130-180	32	0.083	0.127	0.125	0.196	0.028	0.005
180-230	16	0.094	0.125	0.123	0.170	0.021	0.005
230-380	13	0.094	0.149	0.142	0.184	0.026	0.007

A one-way ANOVA was conducted to analyse the effect of depth on soil bulk density (g cm^{-3}). This showed that there was a significant effect of depth on soil bulk density (g cm^{-3}) [F (6, 278) = 13.859, p = <0.001].

Post hoc comparisons using the Tukey HSD test (see Table 6-2) indicated that the mean bulk density (g cm^{-3}) was significantly higher at 0-15 cm depth than at 15-30 cm, 30-80 cm, 80-130 cm, and 130-180 cm depths; significantly lower at 15-30 cm depth than at 30-80 cm, 130-180 cm, and 230-380 cm; significantly lower at 30-80 cm than at 230-380 cm; and significantly lower at 80-130 cm than at 230-380 cm.

Table 6-2: Results of post hoc comparisons using Tukey HSD test

Depth cm	0-15	15-30	30-80	80-130	130-180	180-230	230-380
0-15		*	*	*	*		
15-30			*		*		*
30-80							*
80-130							*
130-180							
180-230							
230-380							

* The mean difference is significant at the 0.05 level.

6.1.2. Spatial variation in soil bulk density with site

The spatial variation in soil bulk density between 'sites' (see Figure 4-1) was investigated. Sites were assigned based on the existing Environment Agency water body sub-catchments. Figure 6-3 shows that the mean soil bulk density (g cm^{-3}) is highest at Highshore Clough (0.084 g cm^{-3}) and lowest at Derwent (Westend to Wye) (0.068 g cm^{-3}). An Independent-Samples Kruskal-Wallis Test showed that there was no effect of site on soil bulk density (g cm^{-3}) ($p = 0.676$).

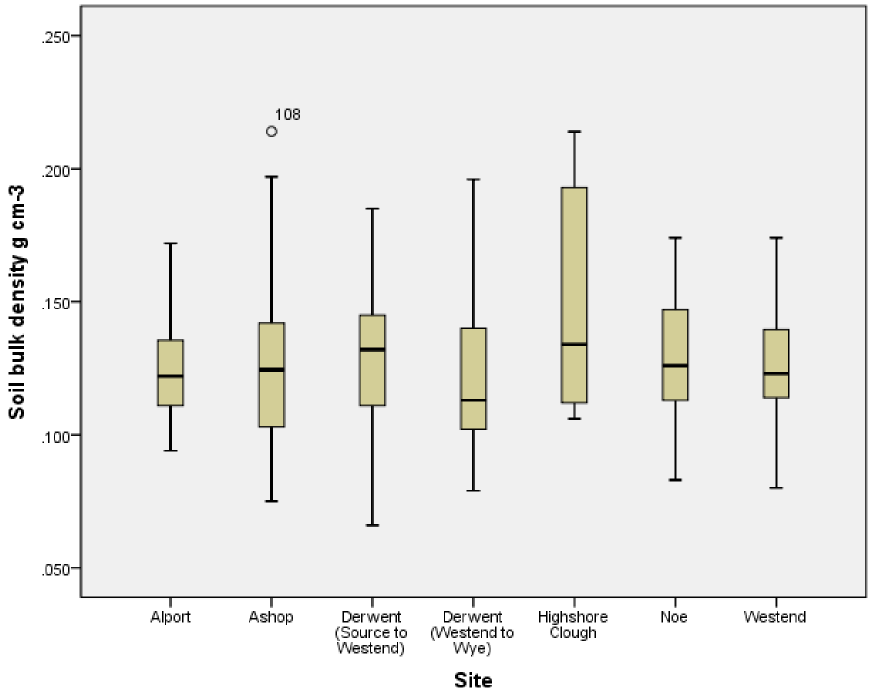

Figure 6-3: Boxplot showing soil bulk density by site

6.2. Carbon concentration

Carbon concentration (g cm^{-3}) was calculated using Equation 1 (Emmett et al., 2008):

Equation 1: Carbon concentration

Carbon concentration (g cm^{-3}) = bulk density (g cm^{-3}) x carbon content (%) / 100

6.2.1. Spatial variation in soil carbon concentration with depth

The mean carbon concentration (g cm^{-3}) at 0-15 cm depth was 0.076 g cm^{-3}. It then dropped to 0.060 g cm^{-3} at 15-30 cm depth, remained steady at between 0.070 and 0.074 g cm^{-3} at 30-230 cm depth, before rising again to 0.087 g cm^{-3} at 230-380 cm depth (see Figure 6-4, Figure 6-5 and Table 6-3).

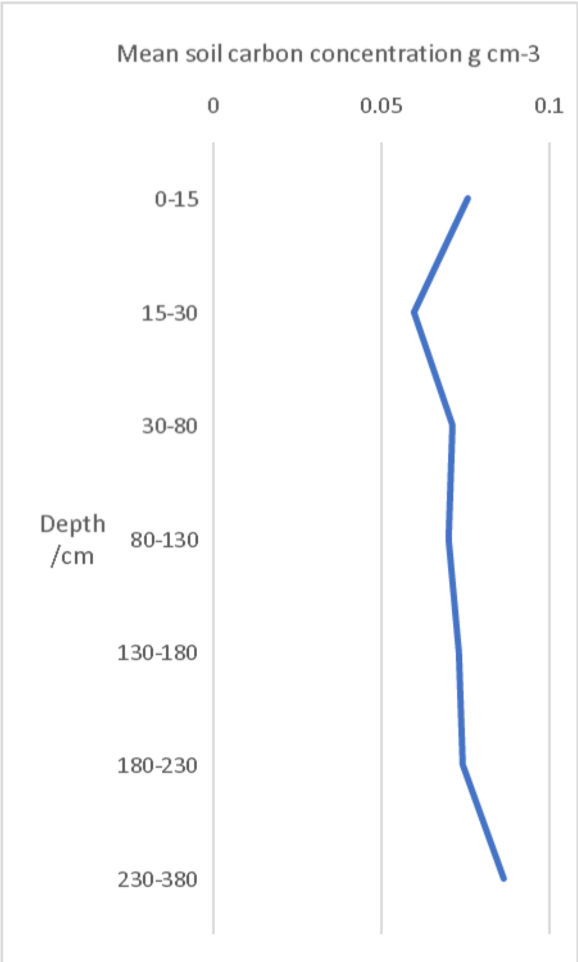

Figure 6-4: Mean soil carbon concentration (g cm^{-3}) with depth

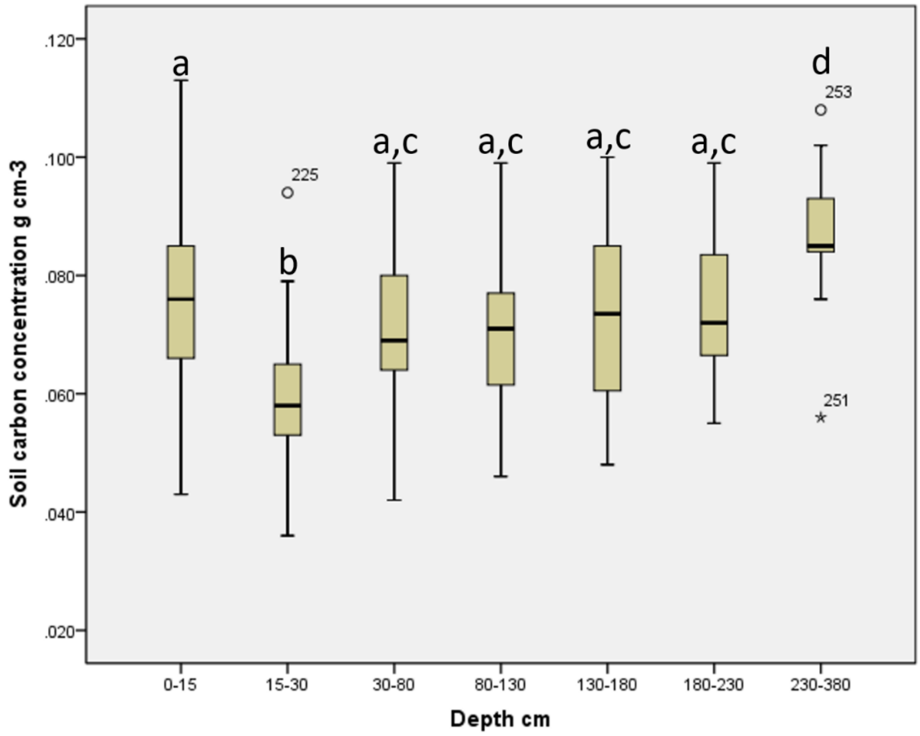

Figure 6-5: Boxplot showing soil carbon concentration with depth. Outliers are indicated with circles and values, categories which share a letter are not significantly different (p<0.05).

Table 6-3: Summary statistics for soil carbon concentration (g cm^{-3})

			Soil carbon concentration (g cm^{-3})					
Depth / cm	N	Mean C %	Min	Max	Mean	Median	Standard deviation	Standard error
0-15	67	53	0.043	0.113	0.076	0.076	0.014	0.002
15-30	66	55	0.036	0.094	0.060	0.058	0.011	0.001
30-80	60	57	0.042	0.099	0.071	0.069	0.013	0.002
80-130	49	58	0.046	0.099	0.070	0.071	0.013	0.002
130-180	33	58	0.048	0.100	0.074	0.074	0.015	0.003
180-230	17	59	0.055	0.099	0.074	0.072	0.012	0.003
230-280	13	58	0.056	0.108	0.087	0.085	0.013	0.004

A one-way ANOVA was conducted to compare the effect of depth on soil carbon concentration (g cm^{-3}). This showed that there was a significant effect of depth on soil carbon concentration (g cm^{-3}) [F (6, 278) = 11.994, p = <0.001].

Post hoc comparisons using the Tukey HSD test (see Table 6-4) indicated that the mean carbon (g cm^{-3}) was significantly lower at 15-30 cm depth than at all other depths, and that carbon (g cm^{-3}) was significantly higher at 230-380 cm depth than at 30-80, 80-130 and 130-180 cm depth.

Table 6-4: Results of post hoc comparisons using Tukey HSD test

Depth cm	0-15	15-30	30-80	80-130	130-180	180-230	230-380
0-15		*					
15-30			*	*	*	*	*
30-80							*
80-130							*
130-180							*
180-230							
230-380							

* The mean difference is significant at the 0.05 level.

6.2.2. Spatial variation in soil carbon concentration with site

Figure 6-6 shows that the mean carbon concentration (g cm^{-3}) is highest at Highshore Clough (0.084 g cm^{-3}) and lowest at Derwent (Westend to Wye) (0.068 g cm^{-3}). An Independent-Samples Kruskal-Wallis Test showed that there was no effect of site on soil carbon concentration (g cm^{-3}) ($p = 0.589$).

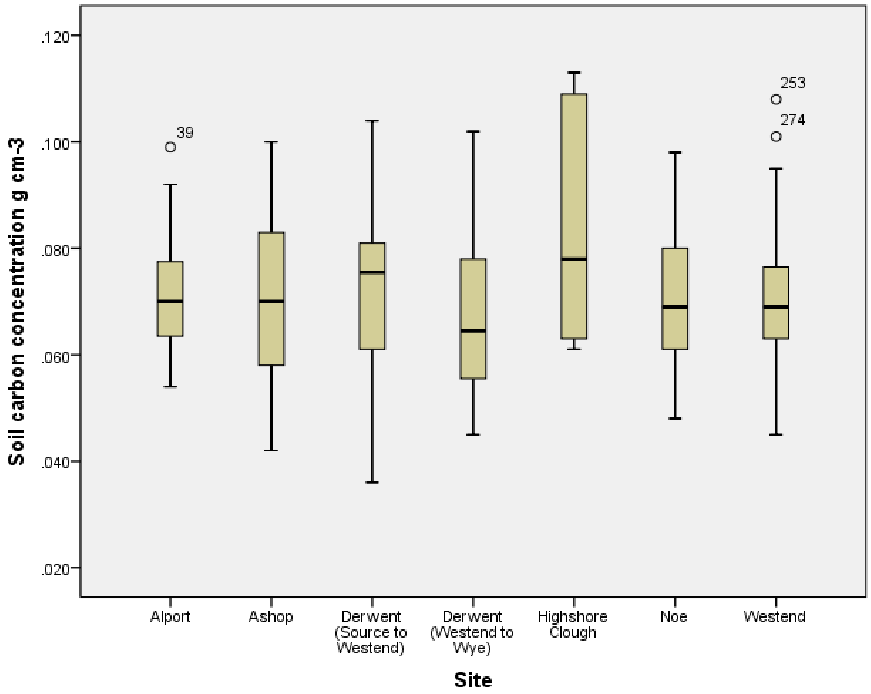

Figure 6-6: Boxplot showing soil carbon concentration by site

6.3. Shallow peat and clay

In five locations, shallow peat was found to be underlain by clay. The mean soil bulk density of the clay samples was 0.814 g cm^{-3} and the mean soil carbon content of these samples was 8%; however, when the mean soil carbon concentration (g cm^{-3}) was calculated using Equation 1, a mean value of 0.057 g cm^{-3} was obtained, which is within the range found for the peat samples (see Table 6-5).

Table 6-5: Summary statistics for clay samples

Variable	N	Min	Mean	Median	Max	Standard deviation	Standard error
Bulk density g cm^{-3}	6	0.616	0.814	0.741	1.222	0.227	0.093
Carbon %	6	1.494	8.077	5.657	16.127	6.248	2.551
Carbon g cm^{-3}	6	0.018	0.057	0.042	0.107	0.036	0.015

The mean soil bulk density of the generally shallow peat overlaying the clay was 0.255 g cm^{-3}; the mean carbon was 32 % or 0.830 g cm^{-3} (see Table 6-6).

Table 6-6: Summary statistics for shallow peat samples

Variable	N	Min	Mean	Median	Max	Standard deviation	Standard error
Bulk density g cm^{-3}	5	0.218	0.255	0.233	0.318	0.042	0.019
Carbon %	5	23.359	32.435	33.295	44.443	8.805	3.938
Carbon g cm^{-3}	5	0.056	0.083	0.073	0.117	0.026	0.012

All of these samples had extreme outlying values for soil density and as such were excluded from the soil bulk density and carbon concentration results presented in sections 6.1 and 6.2 above. However, there is an increasing body of evidence suggesting that a substantial but largely unmeasured amount of carbon passes downwards from the peat deposit to become stored in the mineral sub-soils beneath (Lindsay, 2010). For this reason, in the current study, the clay and shallow peat samples were included in the calculation of the soil carbon stock (see section 6.4 below).

6.3.1. Relationship between soil bulk density, soil moisture content, soil carbon concentration and peat depth

The relationship between the variables in Table 6-7 were explored using Pearson correlation.

Table 6-7: Results of Person correlation

Variable	Bulk density (BD) g cm^{-3}	Soil moisture (SM) %	Carbon (C) %	Carbon (C) g cm^{-3}	Peat depth (PD)
BD g cm^{-3}		P < 0.01	P < 0.01	P < 0.01	P > 0.05
SM %			P > 0.05	P < 0.01	P > 0.05
C %				P < 0.01	P < 0.01
C g cm^{-3}					P > 0.05
PD					

There was a negative linear relationship between soil bulk density (g cm^{-3}) and soil moisture (%). This means that as bulk density decreased, soil moisture increased (Figure 6-7). A Pearson correlation was used to measure the strength of this relationship. This showed that there was a weak but significant correlation between the two variables ($r(285) = -0.286$, $p < 0.01$).

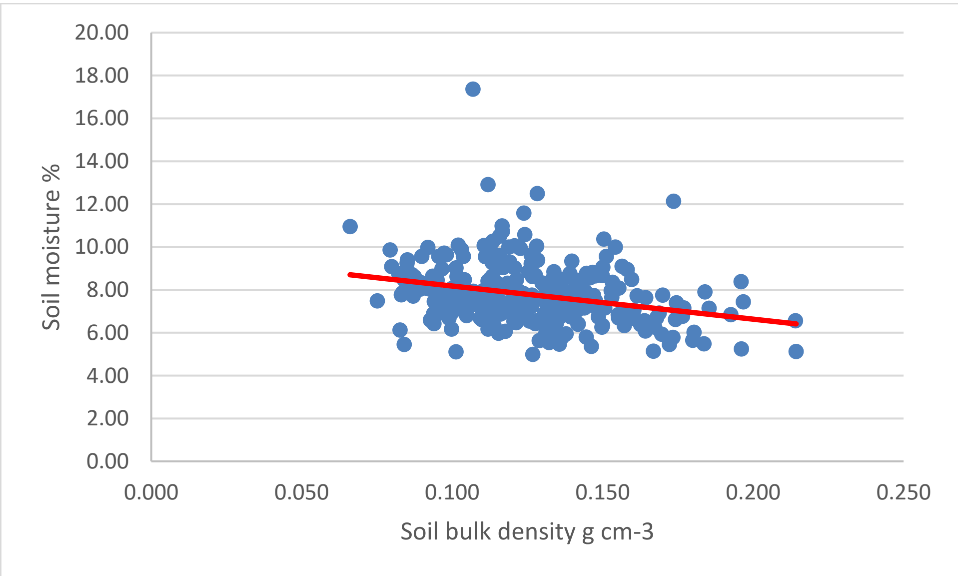

Figure 6-7: Relationship between soil bulk density and soil moisture

There was also a negative linear relationship between soil bulk density (g cm^{-3}) and carbon content (%). This means that as bulk density decreased, carbon content increased (Figure 6-8). A Pearson correlation showed that there was a weak but significant relationship between the two variables ($r(285) = -0.172$, $p < 0.01$).

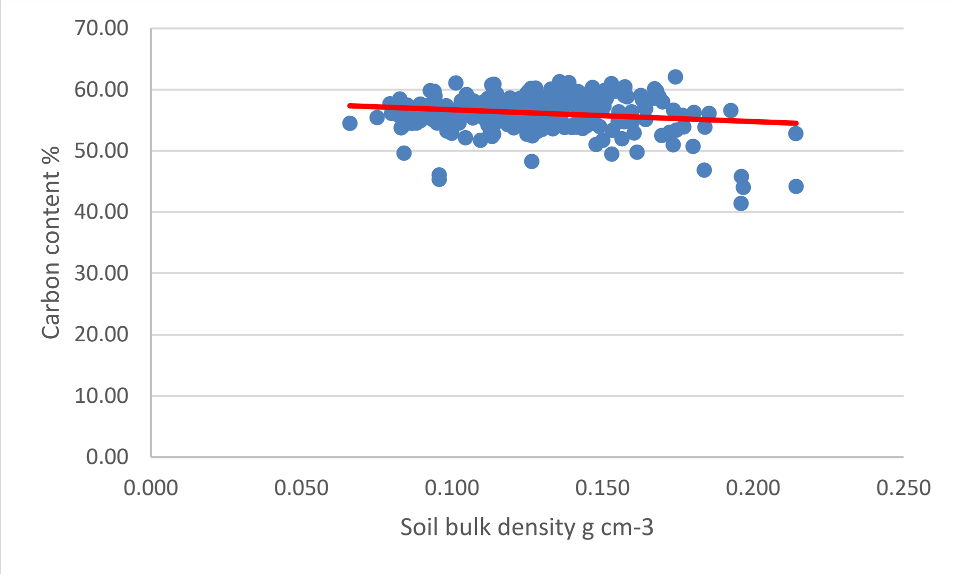

Figure 6-8: Relationship between soil bulk density and carbon content

There was a positive linear relationship between soil bulk density (g cm^{-3}) and carbon concentration (g cm^{-3}). This means that as soil bulk density values increase, carbon concentration values increase (see Figure 6-9). A Pearson correlation showed that the two variables were strongly correlated, ($r(285) = 0.952$, $p < 0.01$).

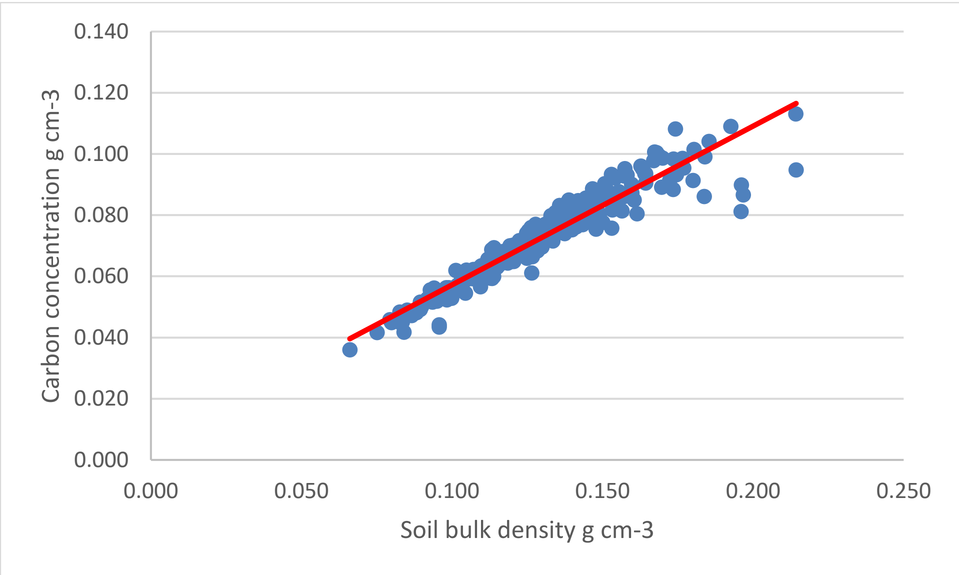

Figure 6-9: Relationship between soil bulk density and carbon concentration

There was no correlation between bulk density (g cm^{-3}) and peat depth ($r(285) = 0.014$, $p = 0.817$), and no correlation between soil moisture (%) and carbon content (%) ($r(285) = 0.044$, $p = 0.463$).

There was a negative linear relationship between soil moisture and carbon concentration (g cm^{-3}). This means that as soil moisture decreased, carbon concentration (g cm^{-3}) increased (Figure 6-10). A Pearson correlation showed that this is a weak but significant relationship ($r(285) = -0.275$, $p < 0.01$).

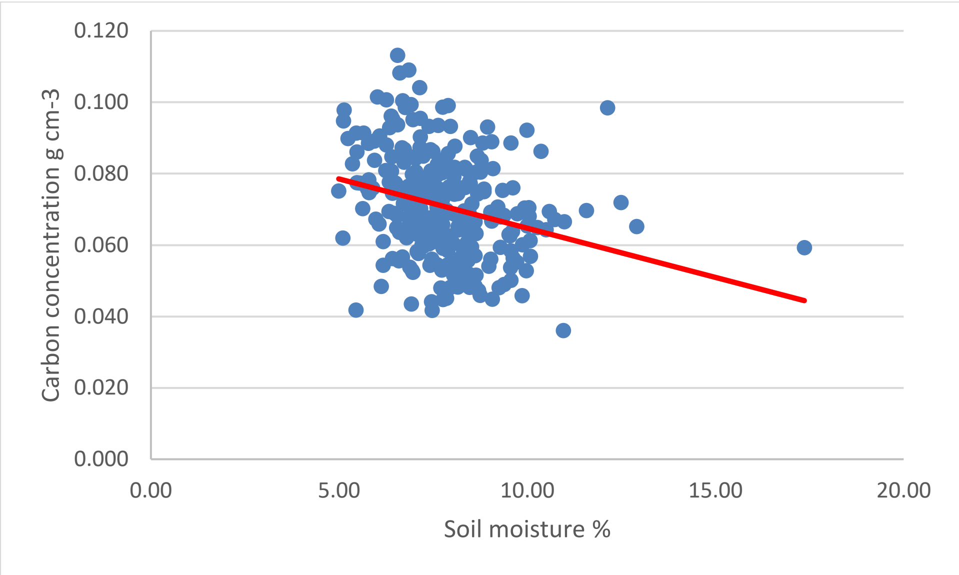

Figure 6-10: Relationship between soil moisture and carbon concentration g cm^{-3}

No correlation was found between soil moisture and depth ($r(285) = 0.001$, $p = 0.991$).

There was a positive linear relationship between carbon content (%) and carbon concentration (g cm^{-3}). This means that as carbon content increased carbon concentration (g cm^{-3}) increased (Figure 6-11). A Pearson correlation showed that there was a weak but significant relationship between the two variables ($r(285) = 0.130$, $p < 0.05$).

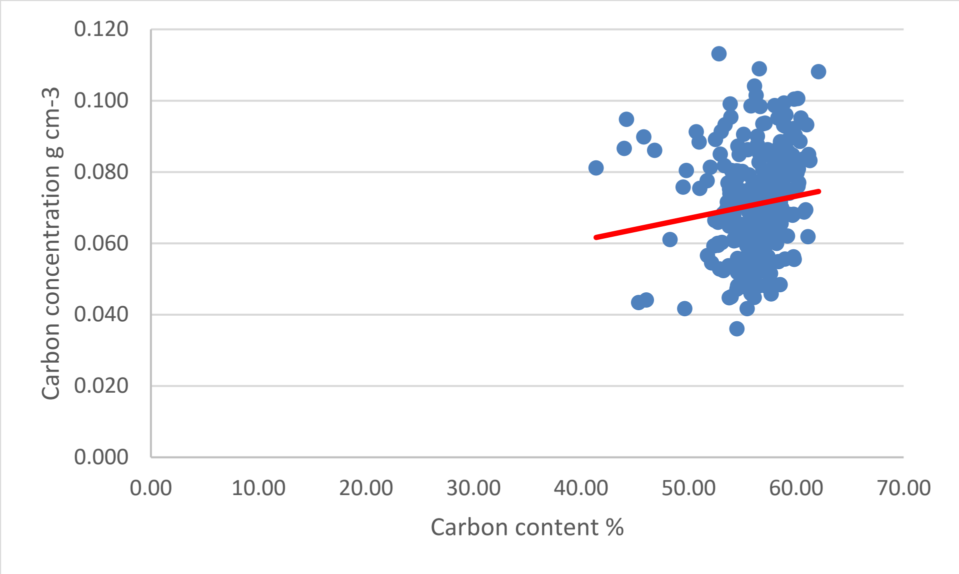

Figure 6-11: Relationship between carbon content and carbon concentration

There was a positive linear relationship between carbon content (%) and peat depth. This means that carbon content (%) increased with depth (Figure 6-12). A Pearson correlation showed that this was a significant relationship ($r (285) = 0.621$, $p < 0.01$).

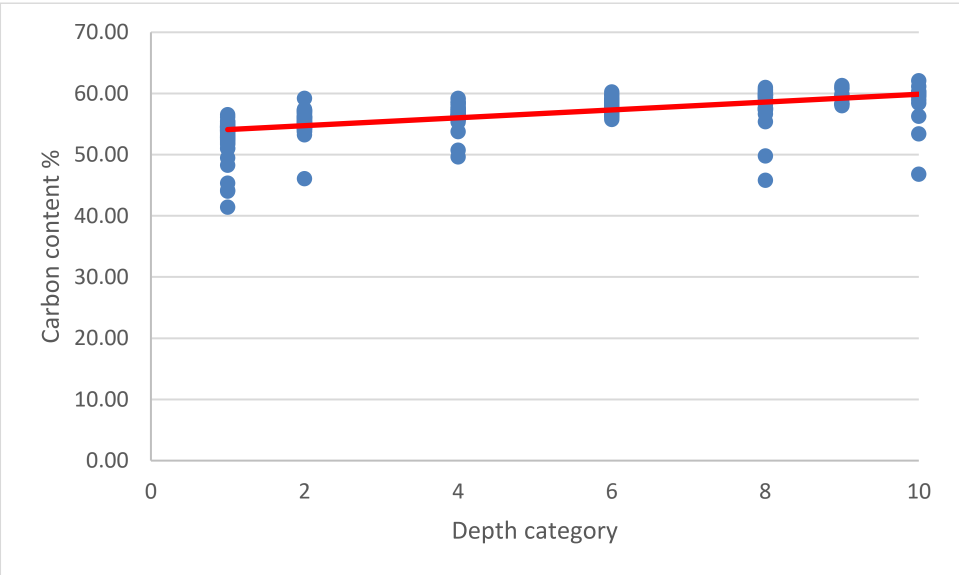

Figure 6-12: Relationship between carbon content and peat depth category (1 = 0-15; 2 = 15-30; 4 = 30-80; 6 = 80-130; 8 = 130-180; 9 = 180-230; 10 = 230-380)

Finally, there was a positive linear relationship between carbon concentration (g cm^{-3}) and peat depth. This means that carbon concentration (g cm^{-3}) increased with depth (Figure 6-13). A Pearson correlation showed that this was a significant relationship ($r (285) = 0.184$, $p < 0.01$).

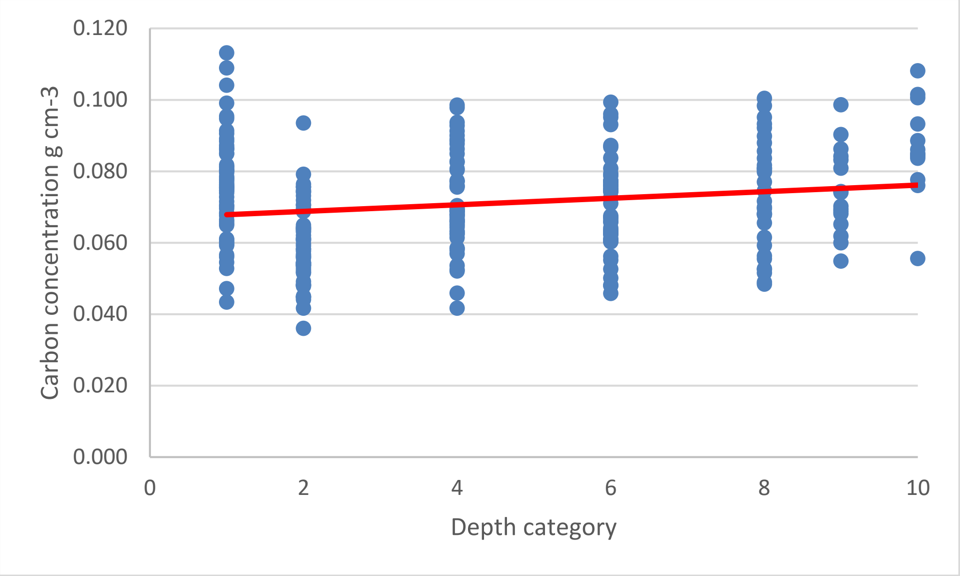

Figure 6-13: Relationship between carbon concentration and peat depth category (1 = 0-15; 2 = 15-30; 4 = 30-80; 6 = 80-130; 8 = 130-180; 9 = 180-230; 10 = 230-380)

6.4. Soil carbon stock

The soil carbon stock was calculated using Equation 2, providing an overall figure for the entire Bamford WTW catchment (Table 6-8), and for each depth category (Table 6-9).

Equation 2: Carbon stock

Carbon stock (g) = area (cm^2) x bulk density (g cm^{-3}) x carbon content (%/100) x depth cm

Table 6-8: Calculation of carbon stocks in the peat soils of the Bamford WTW catchment

Area / cm^2	Mean BD / g cm^{-3}	Mean C / %	Mean depth / cm	C / g	C / T
826,700,000,000	0.148	0.54	137	9.05157E+12	9051571

Table 6-9: Calculation of carbon stocks in the peat soils of the Bamford WTW catchment by depth

Depth / cm	No. of measurements	% of measurements	Area / cm^2	BD / g cm^{-3}	C %	Mean depth / cm	C / g	C / T
0-15	513	100	82,670,000,000,000	0.160	0.51	15	1.01495E+12	1,014,952
15-30	480	94	77,352,046,783,626	0.173	0.51	15	1.02588E+12	1,025,884
30-80	436	85	70,261,442,495,127	0.136	0.55	46	2.422E+12	2,422,003
80-130	336	65	54,146,432,748,538	0.127	0.57	44	1.71556E+12	1,715,563
130-180	250	49	40,287,524,366,472	0.135	0.57	41	1.27641E+12	1,276,405
180-230	172	34	27,717,816,764,133	0.131	0.59	38	8.264E+11	826,400
230-280	89	17	14,342,358,674,464	0.149	0.57	33	3.94928E+11	394,928
280-330	30	6	4,834,502,923,977	0.139	0.61	32	1.34584E+11	134,584
330-380	11	2	1,772,651,072,125	0.174	0.62	9	16053191280	16,053
Total							8.82677E+12	8,826,772

7. Discussion

Clymo (1992) is an often-cited source for 'standard' figures of bulk density in peatlands, giving figures that are characteristic of bog peat. Clymo gives a dry bulk density of 0.03 g cm^{-3} for the acrotelm, and then contrasts this with the denser catotelm layer beneath, citing a dry bulk density value of 0.12 g cm^{-3} for this lower layer (Lindsay, 2010).

According to Chapman et al. (2015), dry bulk density can be quite variable; possible values may range from 0.04 to 0.34 g cm^{-3}, potentially resulting in an eightfold change in the calculation of peat weight. Also dry bulk density may vary with depth, typically being greater at the surface and decreasing lower down the profile in more degraded peats (Frogbrook et al., 2009) but being lesser at the surface and increasing with increasing depth in more pristine peats (see Lindsay, 2010). In the current study, soil bulk density values (0.066 to 0.214 g cm^{-3}, within the range suggested by Chapman et al. (2015)) show the same pattern of higher density in the top section that Frogbrook et al. (2009) found in degraded peatlands.

There is a possibility that the high bulk density in the top 15 cm of bog may have been an effect of compressing the surface layer of peat as the box corer was pushed into the ground. However, the field team took great care to avoid this, and given that an identical effect was seen at all sites, it is more likely that this is a real effect.

This reverse pattern of higher bulk density closer to the surface which deceases with depth was identified in the ECOSSE Report (2007, cited in Lindsay, 2010), which examined bulk density and estimated carbon stocks within two particular study areas. At two study sites (Pumlumon, Wales and Glensaugh, Scotland), figures of 0.2 g cm^{-3} at depths of 0-15 cm depth, and 0.12 g cm^{-3} at depths between 50-65 cm were recorded (Lindsay, 2010).

This is also consistent with the pattern found by Lindsay (2010) of high bulk density (between 0.05 and 0.6 g cm^{-3}) in the uppermost 10-15 cm of the bog; lower bulk density (0.03-0.1 g cm^{-3}), which is often maintained for a considerable depth; and a rise in bulk density at the base of the bog as the basal peat blends into the mineral sub-soil (Lindsay, 2010). Carbon concentration follows a similar pattern to that of bulk density, with a higher carbon concentration in the top 15 cm of the bog (mean 0.076 g cm^{-3}), and falling values deeper in the peat.

One explanation for the high bulk density near the surface is that the acrotelm has been lost, through burning, trampling or drainage (Lindsay, 2010). This results in a 'haplotelmic' bog consisting only of catotelm whose surface layer is now oxidised. The absence of an acrotelm from such sites has important implications for the carbon store, because the acrotelm both protects the existing carbon stock, and adds new material to the catotelm, whereas haplotelmic vegetation (e.g. tussock-forming bog species, wet-heath, dry-heath, bare peat) encourages aeration of the catotelm peat (Lindsay, 2010).

In the current study, no significant difference in bulk density was found between sites suggesting that the peatlands within the Bamford WTW catchment may all be haplotelmic bog.

The current study found a weak but significant negative relationship between bulk density and moisture content and bulk density and carbon content. This is supported by Chapman et al. (2015), who also found a weak but significant negative correlation between bulk density and carbon content. However, they also found that most of the variation in bulk density was explained by the maximum depth (Chapman et al., 2015) but in the current study, no relationship was found between bulk density and depth.

The negative relationship between bulk density and carbon content, whereby as bulk density decreases, carbon content increases, is interesting because the reverse is true once carbon content is converted to carbon concentration. In order to convert carbon content to carbon concentration, bulk density is multiplied by carbon content; therefore, changes in bulk density give rise to large changes in carbon concentration. This is particularly evident when looking at clay samples which typically have a high bulk density and low carbon content, but when the two values are used to calculate carbon concentration these samples have a similar amount of carbon (0.057 g cm^{-3}) as peat samples (0.071 g cm^{-3}) which typically have a lower bulk density and higher carbon content. There is an increasing body of evidence suggesting that a substantial but largely unmeasured amount of carbon passes downwards from the peat deposit to become stored in the mineral sub-soils beneath (Lindsay, 2010). Turunen et al. (1999), in their study of Finnish boreal mires, found that the amount of carbon recorded within the uppermost 70 cm of the underlying mineral sub-soil was equivalent to an additional peat thickness of 18 cm, and they estimated that the total held within this store for Finland may amount to 300 Tg of carbon. This represents 5% of the total store associated with Finnish peatlands. For this reason, in the current study, the clay and shallow peat samples were included in the calculation of the soil carbon stock.

In order to estimate peat carbon stock, data is required on bulk density, carbon content and peat depth. In the UK and England, estimates of peat carbon stocks are highly uncertain due to the substantial variation in the depth of peat soils, which typically ranges from 0.4-6m (Gregg et al., 2021). The UK also lacks a systematic survey approach to determine the extent and depth of peats (Lindsay, 2010). Fortunately, for the current study, a thorough peat depth survey of the Bamford catchment was undertaken in 2011 (Crouch et al., 2011) and the data from that survey was used in the estimate of carbon stocks.

Carbon stock was calculated in two ways: firstly, the carbon stock of the entire Bamford WTW catchment was estimated and secondly, the carbon stock was calculated for each depth category. In the first calculation, the mean value for bulk density and carbon content were 0.148 g cm^{-3} and 54 % respectively. For comparison, Chapman et al. (2015), suggest values of 0.122 g cm-3 for bulk density and 48.5 % for carbon content, while Lindsay (2010) suggests 52% for carbon content as a typical value for the carbon content of blanket mire peat in the UK. In the second calculation, mean bulk density and carbon content ranged from 0.127-0.174 g cm^{-3} and 51-62 % respectively. This gave estimates of 9,051,571 t C and 8,826,772 t C respectively, or 1,095 t C ha^{-1} and 1068 t C ha^{-1}. These values are somewhat higher than values reviewed by Natural England (2021), which ranged from 653 to 944 t C ha^{-1}.

To summarise, a number of important findings have arisen from this study:

1. The soil bulk density and carbon concentration of peat within the Bamford WTW catchment follows a similar pattern: high in the uppermost layer of the bog, lower in the main peat body, and higher at the base of the bog.
2. The high bulk density near the surface suggests that the acrotelm has been lost, resulting in a haplotelmic bog, consisting only of catotelm.

3. There is a strong positive linear relationship between bulk density and carbon concentration. This demonstrates the importance of accurate soil bulk density values when estimating the carbon stored within peatlands.
4. It is estimated that approximately 9,000,000 t C is stored within the peat soils of the Bamford WTW catchment, which equates to approximately 1000 t C ha^{-1}.

8. Project evaluation

The current survey was aligned with the previous peat depth survey. Initially, a ratio of 1:6 for bulk density to depth sampling (Smith et al., 2009, cited in Chapman et al., 2015) was proposed which resulted in 85 cores and provided an even distribution across the site. At this stage landowner permission and NE consent was requested; this meant that no additional/alternative locations could be included without once again seeking permission. The number of locations were too numerous to cover within the budget and timeframe of the project; therefore the locations were reduced by removing any locations with a measured peat depth of less than 50cm, leaving 67 locations. In hindsight, it may have been preferable to refine the locations by topographic location, for example choosing first those locations on 'intact vegetation' over those on gully sides etc. This is because once in the field if the surveyors arrived at a location on a gully side, they would move a short distance onto the intact top as this avoided obtaining a core with a sloping top, which could affect the volume of the sample and make sample preparation more challenging.

9. Reference list

ARCA (2014) 'Russian' D-Section Peat Corer. The Department of Archaeology, The University of Winchester. http://d284f45nftegze.cloudfront.net/PhilStastney/Russian%20peat%20sampler%20datasheet.pdf. Accessed 15 June 2021.

Chapman, S.J., Artz, R.R.E., and Poggio, L. (2015) Determination of organic carbon stocks in blanket peat soils in different condition – assessment of peat condition [on-line] https://www.sepa.org.uk/media/162691/sepa_carbonstocks_in_blanket-bog_final_report_a.pdf. Accessed 9 June 2020.

Committee on Climate Change (2020a). *The Sixth Carbon Budget The UK's path to Net Zero* (on-line). The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf. Accessed 30 March 2021.

Committee on Climate Change (2020b). *Sixth Carbon Budget* (on-line). Sixth Carbon Budget - Climate Change Committee (theccc.org.uk). Accessed 30 March 2021.

Crouch, T., Walker, J.S. and Brown, M. (2011) Peat depth and condition across the moorlands within the Bamford water treatment works catchment. Moors for the Future Report, Edale.

Emmett, BA, ZL Frogbrook, PM Chamberlain, R Griffiths, R Pickup, J Poskitt, B Reynolds, E Rowe, P Rowland, D Spurgeon, J Wilson, CM Wood. (2008). Countryside Survey Technical Report No.03/07: Soils Manual v1.0 (on-line). CS Technical Report No 3-07 - Soils Manual v1 (countrysidesurvey.org.uk). Accessed 13 May 2021.

Evans, C., Artz, R., Moxley, J., Smyth, M-A., Taylor, E., Archer, N., Burden, A., Williamson, J., Donnelly, D., Thomson, A., Buys, G., Malcolm, H., Wilson, D., Renou-Wilson, F., Potts J. (2017). Implementation of an emission inventory for UK peatlands. Report to the Department for Business, Energy and Industrial Strategy, Centre for Ecology and Hydrology, Bangor. 88pp.

Frogbrook, Z. L., Bell, J., Bradley, R. I. and Evans, C. (2009) Quantifying terrestrial carbon stocks: Examining the spatial variation in two upland areas in the UK and a comparison to mapped estimates of soil carbon. *Soil Use and Management*: 25 (3): 320-332.

Gregg, R., Elias, J. L., Alonso, I., Crosher, I. E., Muto, P. and Morecroft, M. D. (2021) Carbon storage and sequestration by habitat: a review of the evidence (second edition) Natural England Research Report NERR094. Natural England, York.

IUCN (2021a). *About Peatlands* (on-line). https://www.iucn-uk-peatlandprogramme.org/about-peatlands. Accessed 30 March 2021.

IUCN (2021b). *Peatland addition to the UK GHG inventory adds 3.5% to national emissions* (on-line). Peatland addition to the UK GHG inventory adds 3.5% to national emissions | IUCN UK Peatland Programme (iucn-uk-peatlandprogramme.org). Accessed 30 March 2021.

Joint Nature Conservation Committee (2011). *Towards an assessment of the state of UK Peatlands*, JNCC report No. 445.

Lindsay, R. (2010) *Peatbogs and Carbon: A critical synthesis to inform policy development in oceanic peat bog conservation and restoration in the context of climate change*. Environmental Research Group, University of East London.

Millennium Assessment (2005). *Living beyond our means: Natural assets and human well-being* (online). http://millenniumassessment.org/documents/document.429.aspx.pdf. Accessed 23 October 2012.

Natural England (2010). *England's Peatlands: Carbon storage and greenhouse gases* (online). http://publications.naturalengland.org.uk/publication/30021?category=24011. Accessed 30 March 2012.

PAA (2012) North Pennine AONB Partnership and Natural England National Peat Depth and Storage Project Field Methodology for Peatland Survey. Penny Anderson Associates Limited.

Soil Quality (2021) *Fact Sheets: Total Organic Carbon* (online). http://soilquality.org.au/factsheets/organic-carbon#:~:text=Organic%20matter%20is%20commonly%20and%20incorrectly%20used%20to,are%20components%20of%20organic%20compounds%2C%20not%20just%20carbon. Accessed 22 June 2021.

Turunen, J., Tolonen, K., Tolvanen, S., Remes, M., Ronkainen, J and Jungner, H. (1999). Carbon accumulation in the mineral subsoil of boreal mires. *Global Biogeochemical Cycles*, 13 (1): 71-79.

10. Appendices

10.1. Appendix A: Soil bulk density (g cm^{-3}) outliers

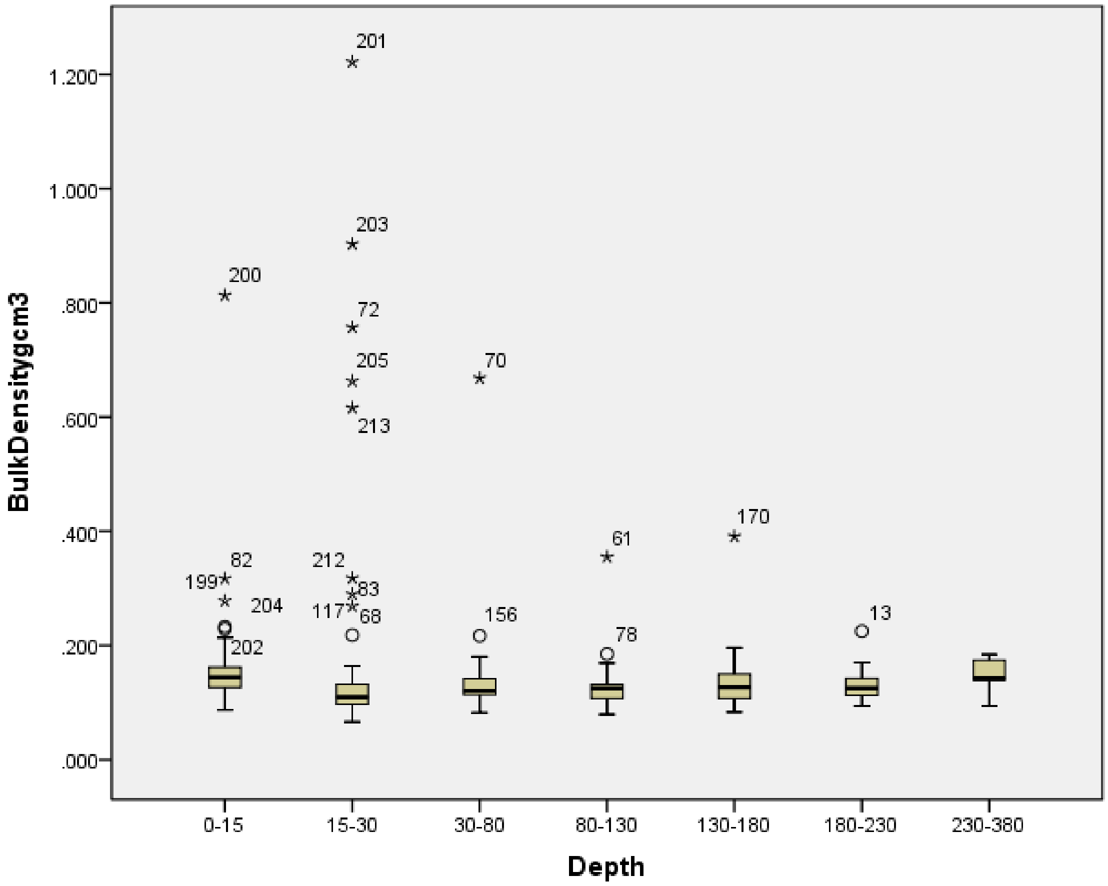

Figure 10-1: Boxplot showing soil bulk density (g cm^{-3}) at different depths

Table 10-1: List of soil bulk density (cm^{-3}) outliers and potential explanation

SPSS ID	Core ID	Depth	Out/Extreme	Explanation	Removed
199	37	0-15	Extreme	Shallow peat (8cm) overlaying clay	Yes
200	37	0-15	Extreme	Clay	Yes
201	37	15-30	Extreme	Clay	Yes
202	49	0-15	Out	Shallow peat (15cm) overlaying clay	Yes
203	49	15-30	Extreme	Clay	Yes
204	91	0-15	Extreme	Shallow peat (15cm) overlaying clay	Yes
205	91	15-30	Extreme	Clay	Yes

61	115	80-130	Extreme	Low soil moisture (2.83%); short sample (18cm); not representative when compared with 50cm sample?	Yes
68	133	15-30	Out	Peat overlaying clay	Yes
70	133	30-80	Extreme	Clay	Yes
212	139	15-30	Extreme	Shallow peat (15cm) overlaying clay	Yes
213	139	15-30	Extreme	Clay	Yes
72	151	15-30	Extreme	Peat containing some clay	Yes
170	157	130-180	Extreme	Low soil moisture (3.56%); short sample (12cm); not representative when compared with 50cm sample?	Yes
78	169	80-130	Out	Short sample (14cm)	Yes
82	193	0-15	Extreme	Field notes report peat as being very dry and crumbly; moisture content within normal range; field notes report gap in sample	Yes
83	193	15-30	Extreme	Field notes report peat as being very dry and crumbly; moisture content within normal range; field notes report gap in sample	Yes
117	277	15-30	Extreme	Low moisture content (3.48%)	Yes
13	349	180-230	Out	Short sample (8cm)	Yes
156	475	30-80	Out	Low soil moisture content (4.04%)	Yes

10.2. Appendix B: Carbon content (%) outliers

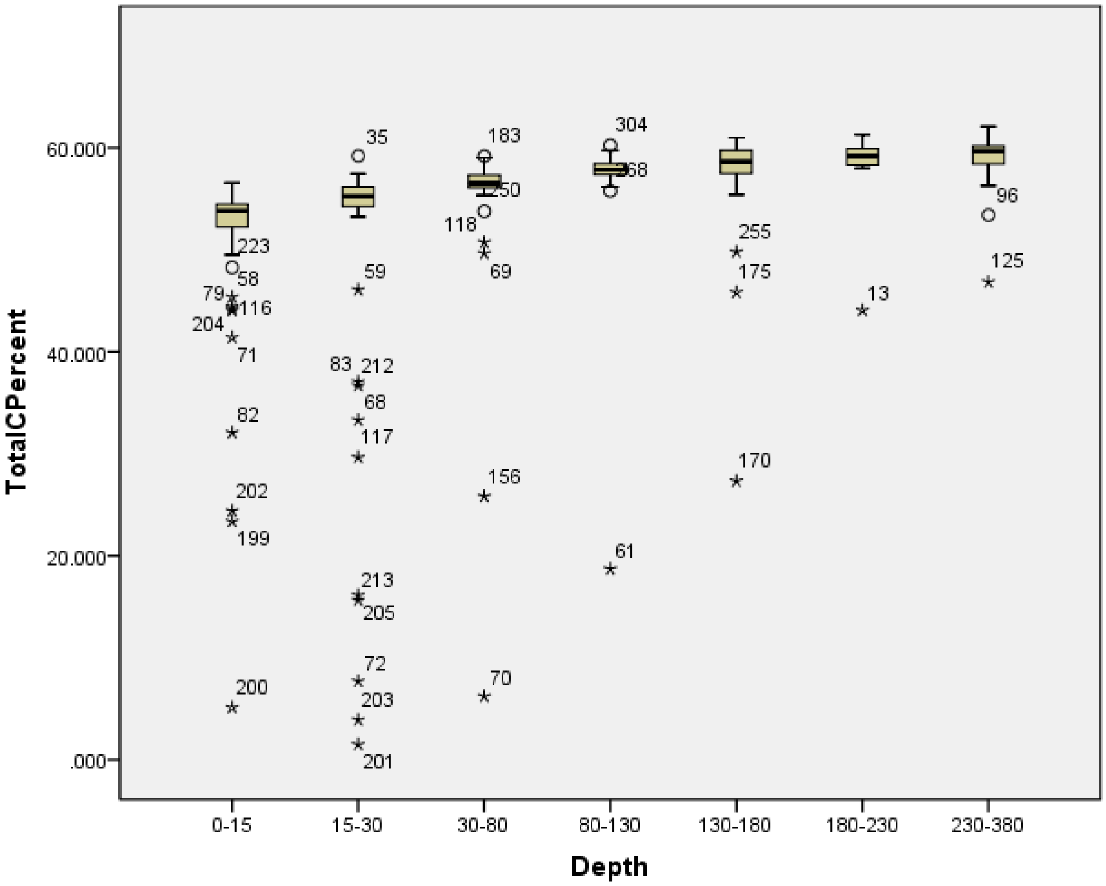

Figure 10-2: Boxplot showing carbon content (%) at different depths

Table 10-2: List of carbon content (%) outliers and potential explanation

SPSS ID	Core ID	Depth	Out/Extreme	Explanation
223	31	0-15	Out	No explanation found
199	37	0-15	Extreme	Shallow peat (8cm) overlaying clay
200	37	0-15	Extreme	Clay
201	37	15-30	Extreme	Clay
202	49	0-15	Extreme	Shallow peat (15cm) overlaying clay
203	49	15-30	Extreme	Clay
204	91	0-15	Extreme	Shallow peat (15cm) overlaying clay
205	91	15-30	Extreme	Clay
58	115	0-15	Out	No explanation found

59	115	15-30	Extreme	No explanation found
61	115	80-130	Extreme	Low moisture content (2.83%); high soil density (0.355); very low carbon 18.70%
68	133	15-30	Extreme	Peat overlaying clay
69	133	30-80	Extreme	Peat (49cm) overlaying clay
70	133	30-80	Extreme	Clay
212	139	15-30	Extreme	Shallow peat (22cm) overlaying peat
213	139	15-30	Extreme	Clay
71	151	0-15	Extreme	Shallow peat (30cm) overlaying clay; field notes report lots of roots and some gaps near the top of the sample.
72	151	15-30	Extreme	Shallow peat containing some clay
170	157	130-180	Extreme	Short sample (12cm); low moisture content (3.56%); high soil density (0.391); very low carbon 27.32%; analysis repeated by lab but same result obtained
79	175	0-15	Extreme	No explanation found
175	187	130-180	Extreme	Short sample (11.5cm); low carbon 45.82%
82	193	0-15	Extreme	Field notes report peat as being very dry and crumbly; moisture content within normal range; field notes report gap in sample
83	193	15-30	Extreme	Field notes report peat as being very dry and crumbly; moisture content within normal range; field notes report gap in sample
96	211	230-280	Out	Short sample (24cm); only out not extreme
250	235	30-80	Out	Short sample (20cm)
183	241	30-80	Out	No explanation found
255	253	130-180	Extreme	Short sample (18cm); low carbon 49.79%
116	277	0-15	Extreme	No explanation found

117	277	15-30	Extreme	No explanation found
118	277	30-80	Extreme	No explanation found
125	307	230-280	Extreme	Short sample (29cm); low carbon 46.4%
268	331	80-130	Out	No explanation; only out not extreme
13	349	180-230	Extreme	Short sample (8cm); high soil density (0.225); low carbon (44.06%)
35	439	15-30	Out	Short sample (22cm)
304	445	80-130	Out	No explanation; only out not extreme
156	475	30-80	Extreme	Low moisture content (4.04%); high soil density (0.217); very low carbon 25.82%; could this be due to peat pipes?

10.3. Appendix C: Carbon concentration (g cm^{-3}) outliers

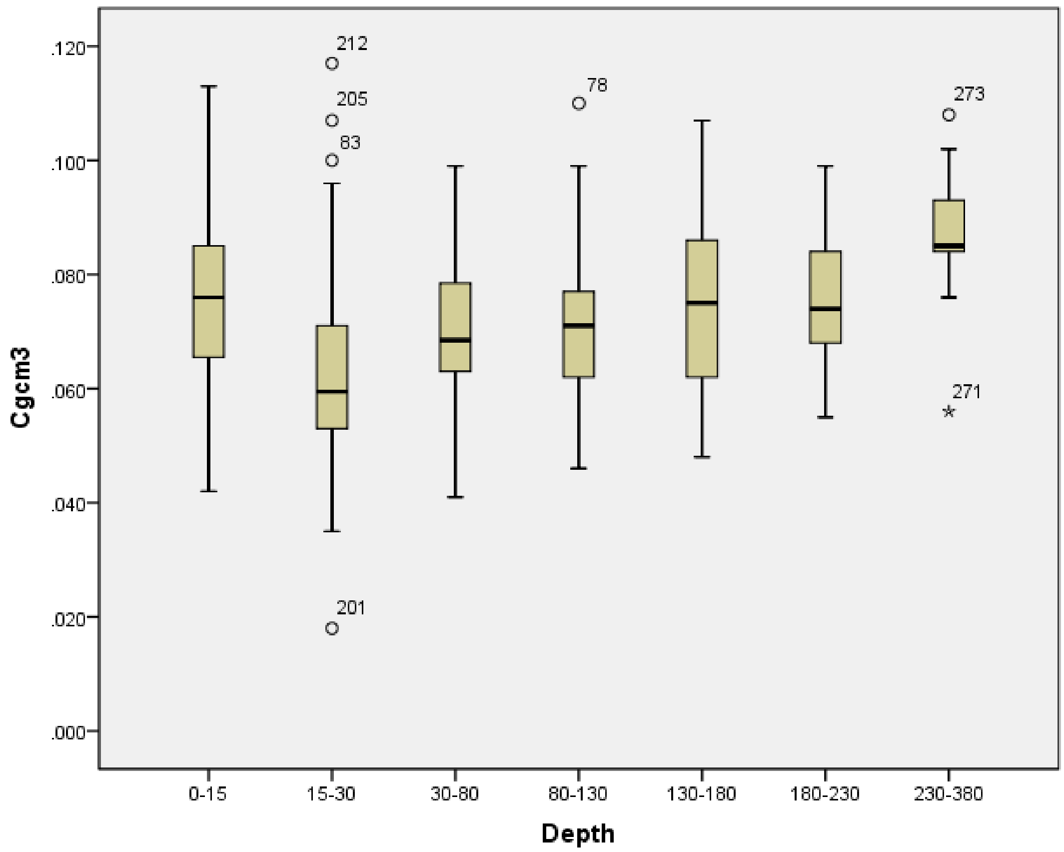

Figure 10-3: Boxplot showing carbon concentration (g cm^{-3}) at different depths

Table 10-3: List of carbon concentration (g cm-3) outliers and potential explanation

SPSS ID	Core ID	Depth	Out/Extreme	Explanation
212	139	15-30	Out	Shallow peat (15cm) overlaying clay
205	91	15-30	Out	Clay
83	193	15-30	Out	Field notes report peat as being very dry and crumbly; moisture content within normal range; field notes report gap in sample
201	37	15-30	Out	Clay
78	169	80-130	Out	Short sample (14cm)
273	331	230-380	Out	Short samples (9cm)
271	331	230-380	Extreme	No explanation found