MoorLIFE 2020

D4 – Estimating Carbon Released from Wildfires:

A case study into the estimated amount of carbon released as a result of the wildfire that occurred on Marsden in April 2019.

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Executive Summary

As part of the MoorLIFE 2020 project, Moors for the Future Partnership (MFFP) aims to monitor the threats to Active Blanket Bog (ABB), of which the primary threat is wildfire. The wildfire that occurred on Marsden and Castleshaw Moors, Yorkshire, in April 2019 caused approximately 666ha of damage to the ABB areas located on site. Wildfires impact on a wide variety of ecosystem services, including carbon sequestration and storage, by releasing the carbon that is stored in peat *(Davies et al, 2013)*, as well as damaging conservation works delivered as part of the MoorLIFE 2020 project. Additionally, the monitoring of carbon emitted to deliver MoorLIFE 2020 is also another key deliverable of the project. Therefore, to understand how the MoorLIFE 2020 carbon emission fits into the wider landscape, the amount of carbon released as part of the wildfire that occurred on Marsden and Castleshaw Moors was estimated, and then compared to the wider literature and how this compares to the amount of carbon released during restoration activities undertaken as part of MoorLIFE 2020.

A variety of factors affects the carbon content of soil, e.g. wetness (*Hendra et al, 2018*), soil bulk density and area (*Lindsay, 2010*) and the amount / type of vegetation present on the site. This variability means that it is difficult to get an accurate assessment of the amount of carbon released as part of this event. Furthermore, due to the unpredictability of wildfires, it is difficult to find other case studies that have been undertaken using direct ground based measurements.

The wildfire on Marsden and Castleshaw Moors was chosen because MFFP has an existing monitoring site located there, measuring a number of variables including peat depth. The monitoring site was located within the area of the burn scar, allowing for peat depth before and after the wildfire to be collected, a key consideration when estimating carbon released as a result of wildfire.

It should be noted that the methodology assumed that the burn depth is equal across the whole site, and therefore causing the same amount of peat loss across the area. This is unlikely to be the case, but is in line with assumptions made by other studies. The burn depth is less likely to be even across this site, as we know the severity of the burn at the monitoring site is not the same as the severity of the burn across the whole site.

The results indicated an estimated 12,483.53 tonnes of carbon was released as a result of the wildfire, based upon the average figures used. Some of this carbon will be converted to pyrogenic carbon, one component of which is black carbon, which will be redeposited on site. When this is taken into account, the total amount of carbon released to the atmosphere is 11,946.74 tonnes. Ninety-eight percent of this came from peat and only two percent from the vegetation lost in the fire. Assuming MFFP standard bare peat restoration techniques are used on the site, then it will take 3.93 years to protect the same amount of carbon through reducing the impacts of erosion.

Carbon was primarily released in the form of carbon dioxide (CO_2) in smoke and fumes, therefore the figure was then converted into CO_2 indicating that 43,844.53 tonnes of CO_2 was released. This is approximately 224.8 times more carbon dioxide than was used to deliver

year 4 of the MoorLIFE 2020 project (195.04 tonnes of CO_2), which to date has seen the most amount of carbon released as a result of our works.

A comparison was made to the fire that occurred on the Roaches in 2018. The Roaches fire was a summer fire which resulted in the loss of more carbon per hectare than the spring fire on Marsden, but due to the larger burn area on Marsden it released more carbon overall.

Contents

List of Figures

List of Tables

List of Equations

1. Introduction

The restoration and protection of peatlands is important because peatlands represent a significant store of carbon (*Davies et al, 2013*), with close to an estimated 20 million tonnes locked up within the peatlands of the Peak District National Park alone *(PDNPA, 2009).* This accumulation of carbon has occurred due to the slow rate of decomposition experienced within this environment as a result of the anaerobic conditions present (*Reddy et al, 2015*).

A key threat to Active Blanket Bog (ABB) is wildfires, which can lead to the release of the carbon that is locked up within them (*Davies et al, 2013*). The South Pennine Moors (SPM) Special Area of Conservation (SAC) has experienced a large number of wildfires in recent years, with 19 instances of wildfire recorded in 2019 *(Titterton et al, 2019)*. With significant numbers of wildfires occurring, a greater amount of carbon will be released into the atmosphere *(Santin et al, 2015).* The wildfires also damage or destroy vegetation *(Davies et al, 2013)*, which causes direct emissions from the vegetation and a longer-term impact of reducing the amount of carbon removed from the atmosphere. The release of these emissions contribute towards global warming *(Berwyn, 2018)*. With the UK government now including greenhouse gas emissions from peatlands in their sixth carbon budget (CCC, 2020), which they aim to cut to net zero by *2050 (UK Government, 2019)*, it is even more important that work is undertaken to reduce the risk and severity of wildfires. This can be done through concrete conservation actions (e.g. gully blocking etc.) and education (e.g. public engagement events).

During a fire, carbon is released in a number of ways, primarily as CO_2 in fumes and smoke; however, some carbon will be converted into pyrogenic carbon termed char *(Clay and Worrall, 2011)*. One component of char is black carbon (charred carbon deposited by vegetation and grassland fires). These latter components may be retained on site.

Due to the unpredictability of where these events occur, it is difficult to obtain empirical data on wildfires. As such, the wildfire that occurred on Marsden and Castleshaw Moors in 2019 represents a rare opportunity to estimate the amount of carbon released during a wildfire event using direct ground based measurements. This is because Moors for the Future Partnership (MFFP) has a monitoring site situated within the burn scar area, collecting a variety of data including peat depth, vegetation data, water table depth, and weather information. The site was established in 2015, allowing before and after data to be collected, a key requirement for determining carbon released due to wildfire. These difficulties are represented in the literature, with it being difficult to find relevant studies looking at carbon released due to wildfires using direct ground measurements for both peatland soils *(Ballhorn et al 2009)* and vegetation (*Lindsay R, 2010*)*.*

In 2019 a similar report to this was written about the impact of a fire on the Roaches that occurred in August 2018 (*Titterton et al 2019a*). MFFP has a monitoring site located within the burn scar of this fire too, collecting the same data as the monitoring site on Marsden. The amount of carbon released during this wildfire was estimated and is included in this report for comparison in section 4.5.

2. Aims and objectives

As part of the MoorLIFE 2020 project, action D4 aims to monitor the threats to ABB, with the primary threat being wildfire, whilst action D5 aims to monitor the carbon emitted in delivering this project. This case study contributed to the delivery of both these actions by demonstrating the carbon impact that wildfires can have on this environment and setting our work in a wider context by:

A. Identifying how much carbon is released through a wildfire event when compared to the activities required to restore an ABB site, which is the focus of action D5.
B. Emphasise the consequences of wildfire and help to reduce the number of accidently started wildfires by increasing awareness of the impact that people's actions can have.
C. Compare the amount of carbon released from wildfire events that occur at different times of year, comparing a spring fire on Marsden (April 2019) with a summer fire on the Roaches (August 2018).

Additionally this work gives us further evidence of the impact wildfire has on this habitat, potentially allowing MFFP to tailor restoration work in the future, e.g. increase the density of *Sphagnum moss spp* planted to increase carbon sequestration (*Harpenslager et al, 2015*).

3. Methodology

3.1 Study Area and Background

The wildfire on Sunday 21st April occurred on a large area of moorland above Marsden, within the National Trust owned Marsden Moor and the neighbouring Common Land, Castleshaw Moor. It is located within the South Pennine Moors, one mile west of Marsden and seven miles south-west of Huddersfield, see Figure 1 below. The site itself is an ABB habitat primarily dominated by grasses including *Molinia Caerulea* (Purple moor grass) with an average of approximately 44% cover, *Eriophorum Vaginatum* (Hare's tail cotton grass) 18% cover and *Eriphorum Angustifolium* (Common cotton grass) 13% cover. There are also limited dwarf shrubs, moorland herbs and mosses present (Moors for the Future Partnership, 2020).

The wildfire was started by a barbecue next to Easter Gate Bridge (sometimes known as Close Gate Bridge), and spread up the hill throughout the ABB area, burning a total of 666ha of ABB. It spread very quickly due to strong winds, damaging vegetation and peat.

As identified in Figure 1 all of the sampling locations were randomly located within the suitable area. The area was selected based upon landowner permission and to ensure that they were located outside both the existing wildfire burn scar perimeter and the perimeter of the wildfire that took place on the site earlier in the year. This ensure that the peat and vegetation were sampled in their pre-fire condition, ensuring the samples reflected what was destroyed by the fire and not what remained after the fire. If a sample point was not suitable due to insufficient peat, it was discounted and the next one in the sequence visited.

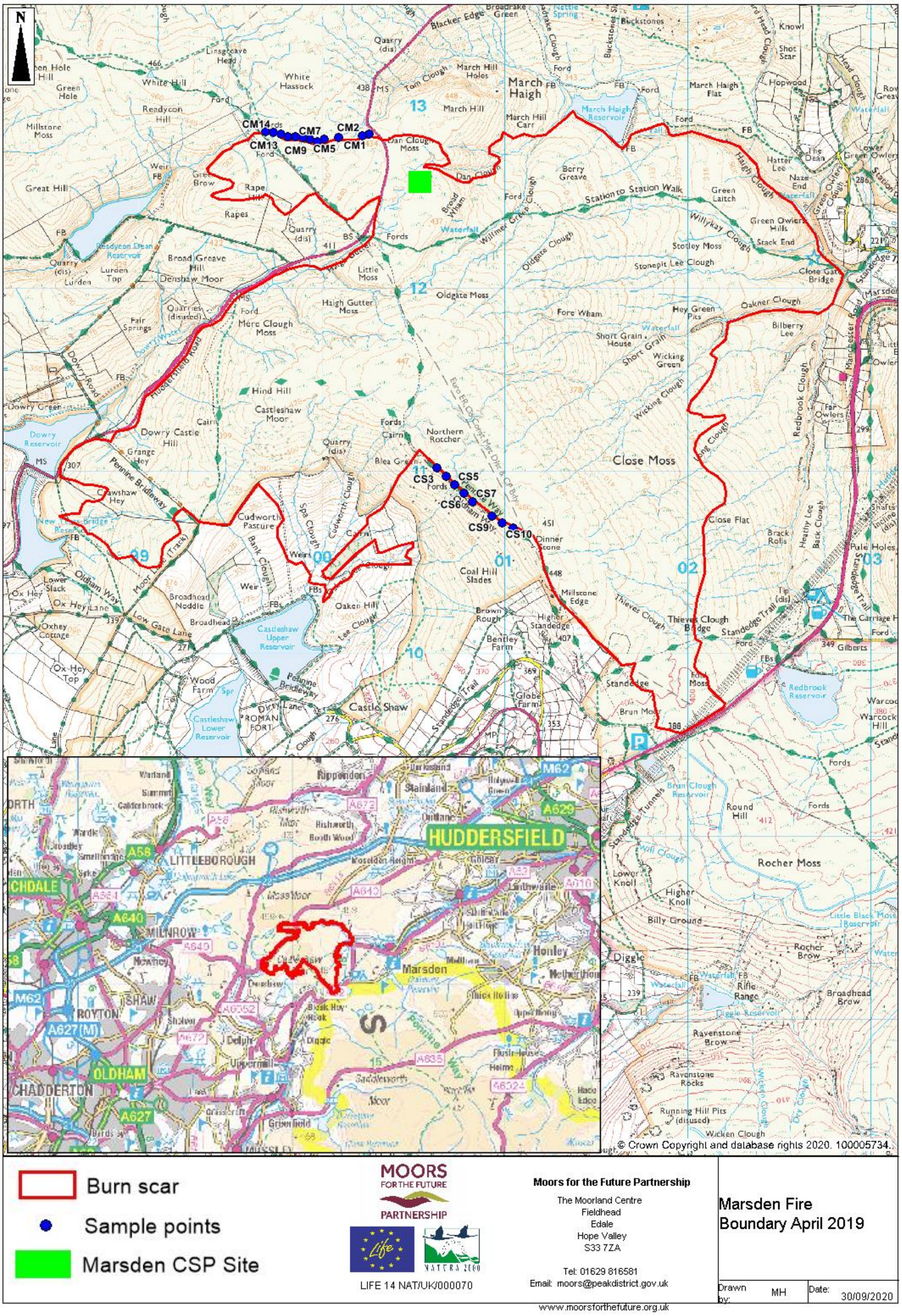

Figure 1 – Location map showing the outline of the burn scar perimeter for the Marsden wildfire in 2019. Inset location of Marsden in the wider context.

3.2 Soil Carbon Methodology

3.2.1 Carbon Released

Equation 1 was used to determine the amount of carbon released as a result of the wildfire.

Carbon released = estimate of burned area*soil bulk density*carbon content*depth of peat burned

Equation 1: Formula for calculating carbon released *(Evans, 2018)*

3.2.2 Estimated Area Burned

The burn scar perimeter was mapped by walking the line of the area burnt using the tracks function on an Etrex 10 GPS. This mapping exercise was undertaken in May 2019. This allowed the burnt area to be calculated in hectares using MapInfo® software. Hectares was then converted into cm^2 to ensure that all units were the same type.

3.2.3 Soil Bulk Density

The soil bulk density was calculated using the methodology described in Rowell *(2014)*. This involved sinking a density ring, 5.5cm in diameter and 4cm in length, into the soil vertically and then digging out the density ring, being careful to leave soil hanging out of the top and bottom of the ring. The excess soil was then carefully removed using a knife leaving an intact core behind. The sample itself was confined to the top 15cm of soil *(Chaudhari et al, 2013; Wood, 2006).*

The site was split into two areas outside the burn perimeter due to the size of the wildfire:

- On National Trust owned land on Close Moss
- On Common Land on Castleshaw, below the Pennine Way

Within each of these areas 15 randomly selected sample locations were identified, which in total provided 30 sample locations. From these 30 locations, 20 samples were taken (see Figure 1 above).

Prior to sampling taking place each density ring, see Figure 2 below, was weighed and numbered so that the correct weights could be attributed to the correct sample.

Density rings are metal rings that are hammered into the soil in order to create a soil core, which can be used for soil bulk density calculations.

Figure 2: Photo and definition of density rings

Once collected the soil samples were dried in an oven at 105°C for 24 hours *(Rowell, 2014)* and then weighed again to obtain the dry soil mass. Next, soil bulk density was calculated using the formula identified in Equation 2 below.

Soil bulk density = mass of oven dry soil / volume of cylinder

Calculation of dry bulk density (using typical data)	(grams)
Mass of cylinder + caps + dry soil	224.28
Mass of cylinder + caps	77.02
Mass of oven dry soil	147.26

E.g. Volume of cylinder = $\pi r^2 L = \pi \times 5.5^2 \times 4 = 95.033$ cm^3.

Therefore, oven-dry bulk density is 147.26/95.033 = 1.55 g cm^3

Equation 2: Soil bulk density calculation example (*Adapted from Rowell, 2014*)

3.2.4 Carbon Content

Twenty soil samples of approximately 100g of peat were collected at the same location as the soil cores and analysed to provide a percentage of carbon content per sample. Forest Research undertook the analysis.

3.2.5 Peat Anchor Data

Data provided from the Community Science project (*Moors for the Future Partnership*, 2020), collected by Marsden Moor National Trust volunteers, enabled peat anchor data pre and post fire to be collected. This involved measuring the distance between the ground and the top of the peat anchor on the northern face, for six different peat anchors spread out across the monitoring site (see Figure 1 for location). The higher the number the larger the difference between the ground and the top of the peat anchor. This has been used to determine the change in surface height.

3.3 Vegetation Carbon Methodology

3.3.1 Carbon content

At all 20 sample sites, see Table 1 below, a minimum of 20g of vegetation was collected for analysis by NRM Laboratories. This represents the smallest sample size that NRM could use to determine the carbon content of the vegetation (*Personal Communications, 2020*). Samples were kept as small as possible to avoid causing any unnecessary damage to the habitat, which complies with the Natural England SSSI (Site of Scientific Interest) consent.

3.3.2 Dry Mass

The dry mass associated with the vegetation sampling locations was collected in two different ways, see Table 1 below.

1. Direct sampling using a 50 x 50cm quadrat
2. Linear regression analysis using smaller samples obtained for the carbon content analysis

Table 1: Sample sites and the methodology used to determine dry mass and vegetation density

Direct sampling sites	**Calculated sampling sites**
CM-1	CM-10
CM-2	CM-11
CS-10	CM-12
CS-11	CM-13
CS-3	CM-14
CS-4	CM-15
CS-5	CM-5
CS-6	CM-7
CS-7	CM-8
CS-9	CM-9

3.3.2.1 Direct sampling methodology

Approximately 1m from where the soil samples was taken, the above ground biomass was harvested by removing all vegetation down to the ground level in a 50cm x 50cm quadrat *(Ordo´n˜ez et al, 2008)*, and stored in a sample bag (*NRCS, Unknown).* The samples were then dried in an oven at 60 degrees for 24 hours and then weighed. The sample was then left to air dry for a further 24 hours to see if the weight changed. As no change in mass was recorded this was deemed to be the dry weight of the samples (*University of Idaho, 2009*).

3.3.2.2 Calculated Samples

For the calculated sample sites, see Table 1 above, the vegetation that was collected for the carbon content was weighed prior to being sent to NRM labs in order to obtain the wet mass, but no dry mass was measured as they were used for the carbon analysis. The dry mass from these samples was worked out using linear regression. It was undertaken this way in order to reduce the number of samples collected and reduce the impact to the habitat.

3.3.3 Carbon Released

Once all data was collected, the calculation in Equation 3 was used to determine the amount of carbon released from the above ground vegetation as a result of the wildfire, then this was turned into carbon dioxide released using the calculation in Equation 5.

Carbon released = Vegetation mass x Carbon content x Area burnt

Equation 3: The Calculation used to determine carbon released from the vegetation

3.4 Black Carbon

A proportion of the amount of calculated carbon released from the site post-burn is likely to have been converted into pyrogenic material, including black carbon, and carbon that was not lost to the atmosphere. Black carbon is the charred remains of vegetation and organic material that was not completely burnt during the wildfire. Clay and Worrall (*2011*) estimated that black carbon accounted for 4.3% of the total carbon released during a fire.

Total carbon released to the atmosphere = Total carbon produced*0.957

Equation 4: Total carbon released to the atmosphere calculation

3.5 Carbon Dioxide

Once the amount of carbon released was identified it was converted into carbon dioxide by multiplying total carbon released to the atmosphere by 3.67 *(Evans, 2018),* which is the difference in atomic weight between carbon and carbon dioxide *(EIA, 2020)*.

Total Carbon dioxide lost = Total Carbon released to the atmosphere*3.67

Equation 5: Total carbon dioxide lost calculation

3.6 Assumptions

A number of assumptions have been made when calculating the carbon released as a result of the wildfire including:

<u>Carbon content of ash and other pyrogenic by-products –</u> This study does not calculate the amount of carbon that was re-sequestered, either on site or at locations outside the burn scar perimeter. Carbon can be incorporated back into the soil through geological and biological processes including bioturbation, the actions of organisms like earthworms, and geological process such as freeze thaw cycles (*Bodí et al*, *2014*).

As site specific values for this type of carbon were not calculated, separate values were obtained from a study undertaken in the Peak District National Park (PDNP), specifically Edale, by Clay and Worrall (*2011*). This study looked at the amount of black carbon that was produced as a result of a fire.

An even burn across the site – The study assumed that the wildfire burned evenly across the whole site causing the same amount of peat loss, which we know is not the case. This assumption has been made because before and after peat depth data is not available for the whole burnt area, due to the unpredictability of where wildfire will occur. It should be noted that this is a common problem associated with this type of research and the same assumptions have been made by Ballhorn et al *(2009).*

Based upon the location of the peat anchor data we do have, there is a high likelihood that the depth burnt is an underestimation. This is because all the peat anchors are within a 'low severity' burned area. See Figure 3 for the map of burn severity across the burn scar and Table 2 for proportions of burn severity.

Figure 4 below is an aerial image of part of Castleshaw Moor taken approximately one month after the wildfire occurred showing some unburned tufts of vegetation within the area. The unburned area from Table 2 was removed from the overall burn area.

Table 2: Different levels of burn severity across the site

Burn severity	Area (ha)	Area of total burn scar (%)
High	0.63	<0.1
Moderate-high	35.21	5
Moderate-low	160.01	22.7
Low	470.09	66.8
Unburned	38.06	5.4
Total	**704**	**100**
Total burned	**665.94**	**94.6**

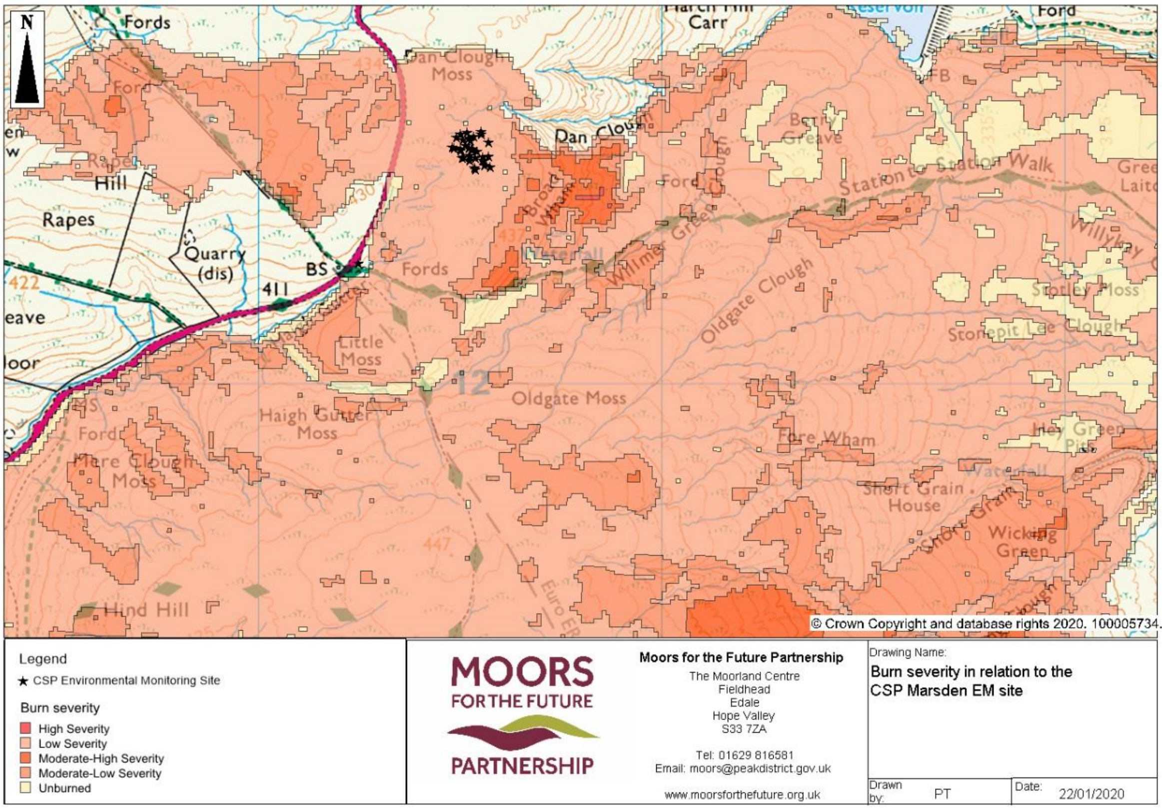

Figure 3: A map showing the burn severity across different areas of the wildfire burn scar in relation to the monitoring site.

Figure 4: An aerial view of an area of the burn scar after the wildfire occurred, taken 23/05/2019

4. Results

4.1 Soil Carbon Data

4.1.1 Peat Anchor Data

Analysis of the peat depth data, see Table 3 below, identified that the peat depth decreased by 15.6 mm on average after the fire. The largest peat depth decrease was 26.5mm and the smallest was 8.5mm. There are ten peat anchors on the monitoring site but only six have sufficient before and after datasets. The data collected in 2018 was anomalous so is not included.

Table 3: Distance between top of the peat anchor and the peat surface pre and post wildfire (mm)

		Peat anchor depth (mm)						
	Date	**MD-P01**	**MD-P02**	**MD-P03**	**MD-P05**	**MD-P09**	**MD-P10**	**Average**
Pre wildfire	**Jul-2016**	220	100	135	168	195	215	
	Aug-2017	220	No record	140	No record	190	215	
Post wildfire	**May-2019**	238	114	147	180	204	220	
	Jun-2020	255	135	145	175	210	230	
<u>Difference Pre & Post wildfire</u>		**26.5**	**24.5**	**8.5**	**9.5**	**14.5**	**10**	**15.6**

4.1.2 Sample Outliers

Six of the twenty samples were removed from analysis because either the carbon content or the bulk density was visibly irregular, see Figure 5 and Figure 6. Five samples had a statistically higher bulk density than the majority of the samples (t-test, $P<0.005$). Six samples had a statistically lower carbon content than the majority of the samples (t-test, $P<0.001$). This is likely because these samples were collected in shallower peat areas near rock causing the peat to have a high mineral content. This was not deemed representative of the fire site, which contains very few rocky areas.

Outliers removed from the soil samples were not removed from the vegetation samples, despite being taken from the same locations. This is because the vegetation would have been burnt regardless of the differing peat depth below.

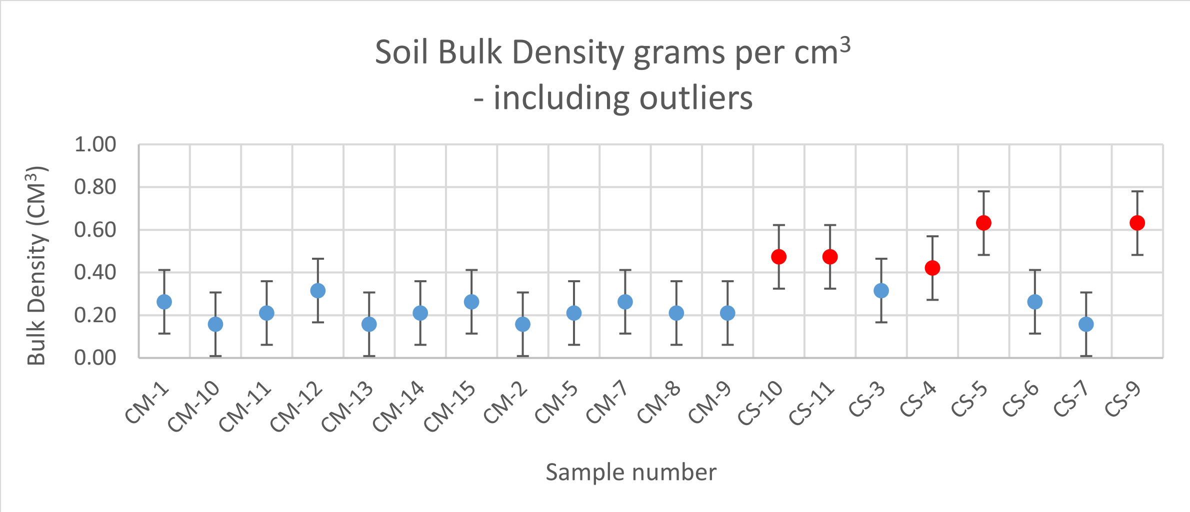

Figure 5: Soil bulk density including outliers in red; t-test P<0.005; Error bars represent standard deviation (P=0.05) away from mean and represents the errors associated with collecting the sample.

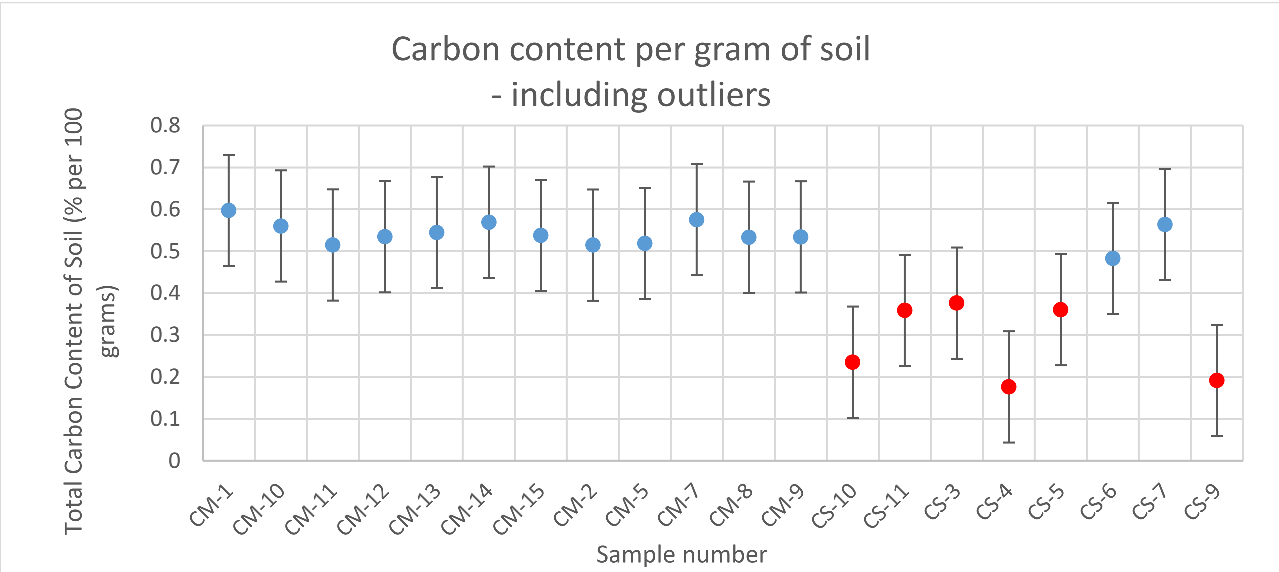

Figure 6 Total Carbon Content per gram of soil including outliers in red, t-test P<0.001. Error bars represent standard deviation (P=0.05) away from mean.

4.1.3 Soil Carbon Content

The carbon content of the samples is provided in Figure 7 below. The highest carbon content recorded was in sample CM-1, which had a carbon content of 0.60 per gram, whereas the lowest recorded carbon content was in sample CS-6 at 0.48 per gram, a range of 0.12.

Additionally 11 out of the 14 samples have a standard deviation within the all site mean, this indicates that the average site figure of 0.54 per gram would be appropriate to use for carbon content across the site, when compared to using minimum or maximum figures obtained from the analysis.

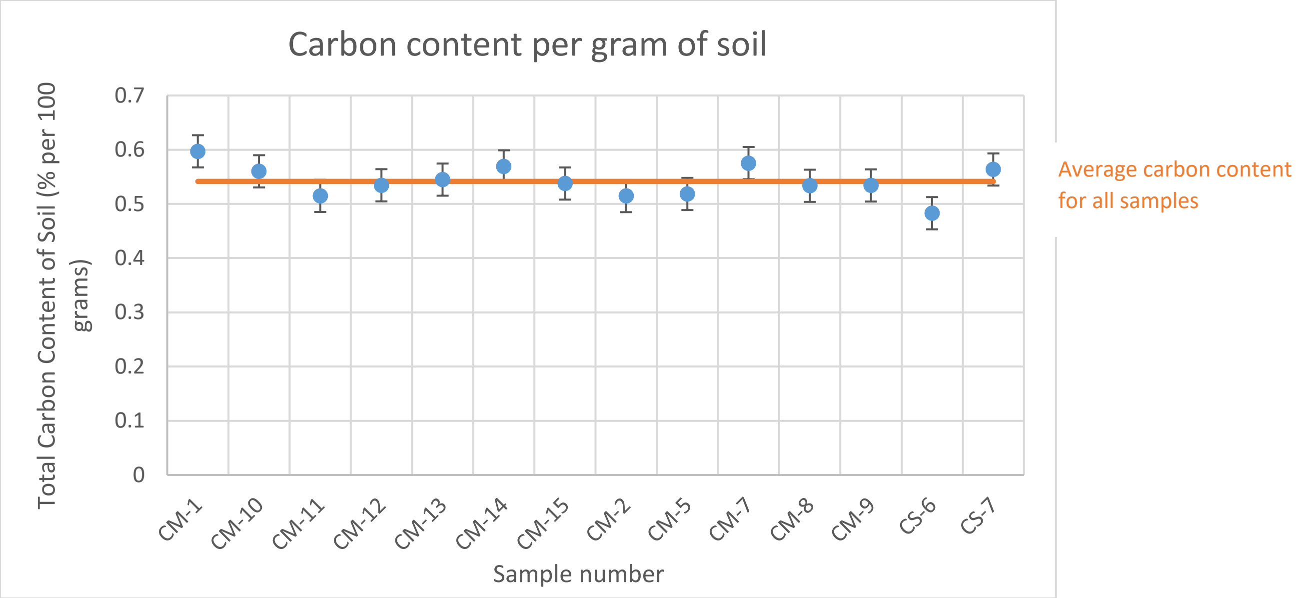

Figure 7: Carbon content per gram for sample locations with the error bars showing the standard deviation (P=0.05) for the mean, for the all site figure, and represents the errors associated with processing the sample.
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4.1.4 Soil Bulk Density

Soil bulk density samples were analysed from 14 locations around the edge of the burn scar perimeter, with nine out of the 14 samples within the standard deviation (0.05cm^3) of the all site average. Six samples are significantly higher than the others suggesting there is variability across the site.

The average soil bulk density for the whole site is 0.22 grams per cm^3, with the highest soil bulk density found in sample CM-12, which is 0.32 grams per cm^3, whereas the lowest bulk density is 0.16 grams per cm^3 in samples CM-2, CM-10, CM-13, and CS-7, see Figure 8 below.

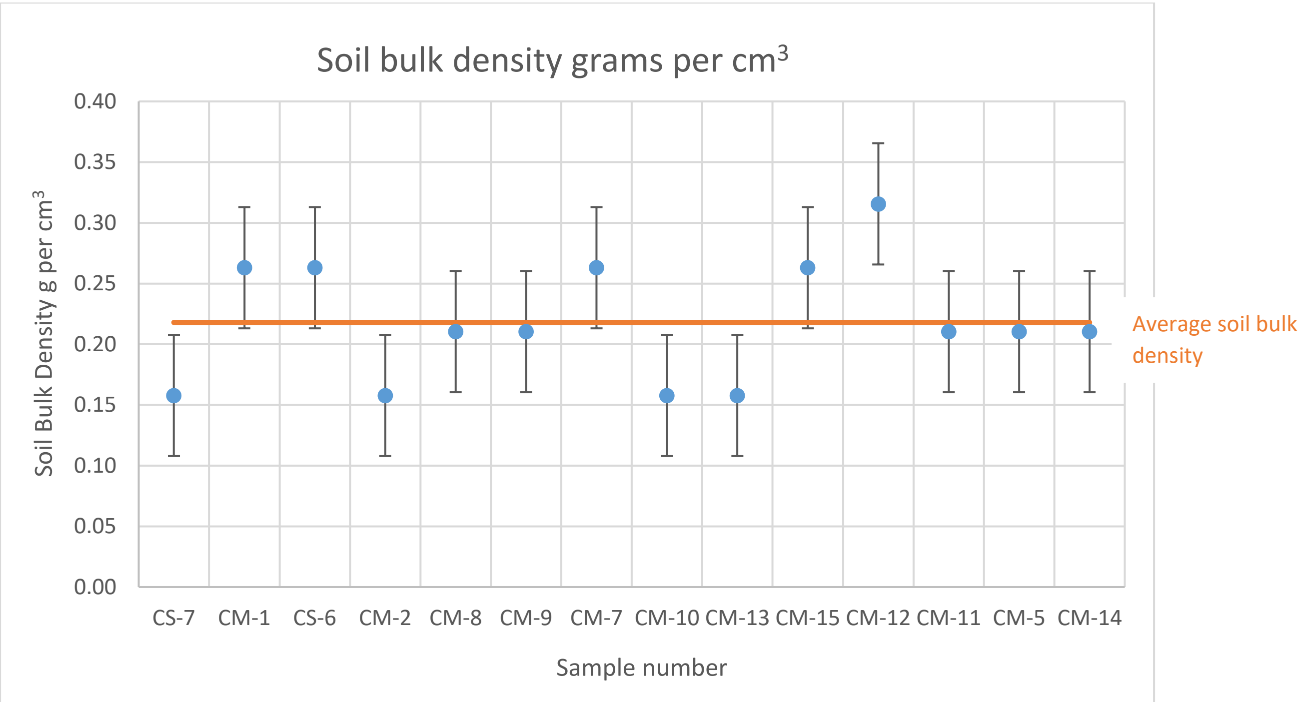


Figure 8: Soil bulk density measurements for the site, error bars represent standard deviation (P=0.05) away from the mean for the whole site average and represent the errors associated with collecting the sample.

4.1.5 Total Carbon Released From Soil

From undertaking the calculation identified in Equation 1 it was possible to determine that the total average carbon released from the soil as a result of the wildfire on Marsden and Castleshaw Moors was 12,246 tonnes of carbon, see Figure 9 below. Maximum and minimum values were also calculated based upon the maximum and minimum figures identified from the carbon content and soil bulk density variables identified above. This produced a range of 28,945 tonnes of carbon, highlighting the difficulty in getting accurate figures.

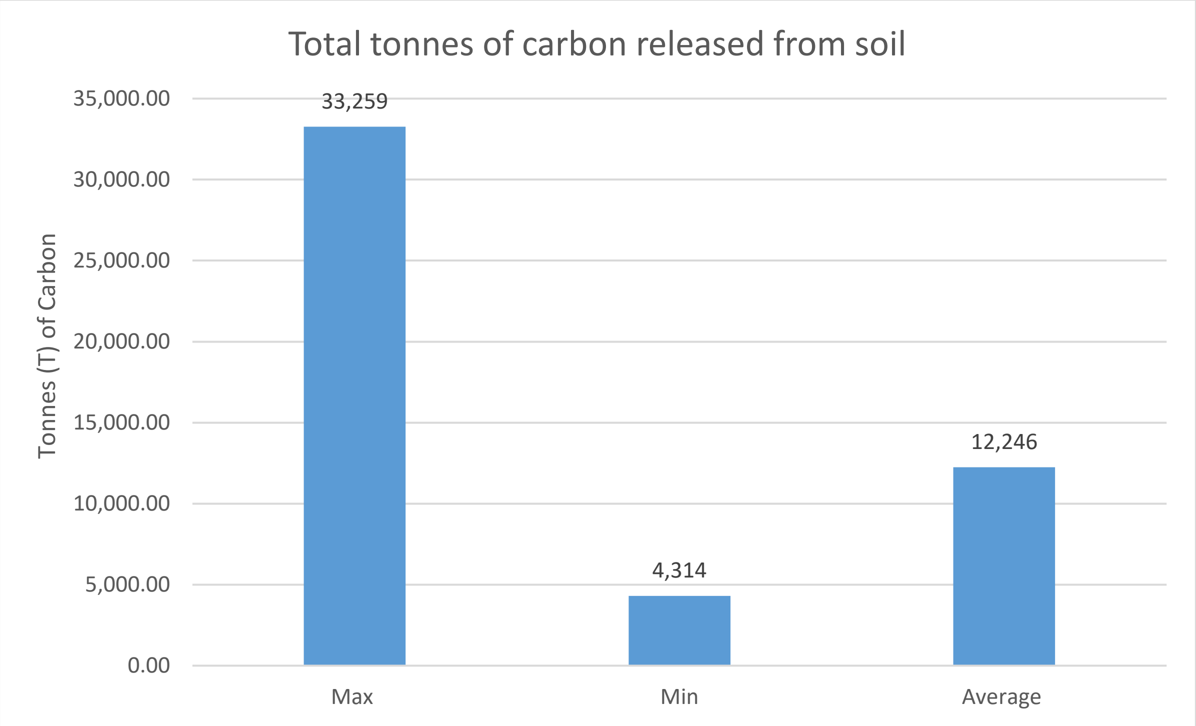


Figure 9: Total tonnes of carbon produced from soil as a result of the wildfire

4.2 Vegetation Carbon Data

4.2.1 Vegetation Carbon Content

Figure 10 below sets out the carbon content associated with the vegetation sampled on site. These data sets show that the carbon content of the vegetation was consistent across all samples, with less than a 2.3% difference between the highest sample (CM13 – 50.8%) and the lowest sample location (CS10 – 48.5%).

The average carbon content of the all samples taken is 49.54%, with a standard deviation of 0.63. This suggest that the average figure is appropriate to use for the overall calculation for carbon released as part of the wildfire.

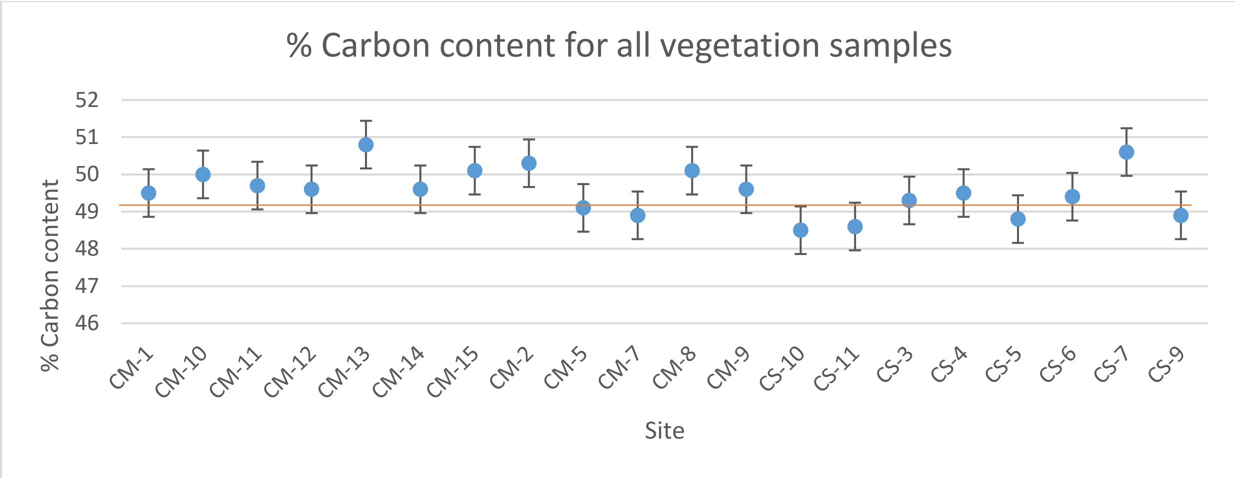


Figure 10: Carbon content for each sample location with the error bars showing the standard deviation (P=0.05) for the mean, for the all site figure and represents the errors associated with collecting the sample.

4.2.2 Vegetation Mass

The wet vegetation mass for the individual samples is presented in Figure 11 below, which indicates that those sites that were sampled directly were on average heavier (73.5 grams) compared to those which were used from the carbon content analysis (29.0 grams), which when combined produced an average weight of 51.25grams.

When looking at the standard deviation for the calculated figures (Graph 11.2) we get a figure of 9.66, whereas for the blue samples (graph 11.1) the figure is 27.99. When looking at all samples together we get an average standard deviation of 30.66.

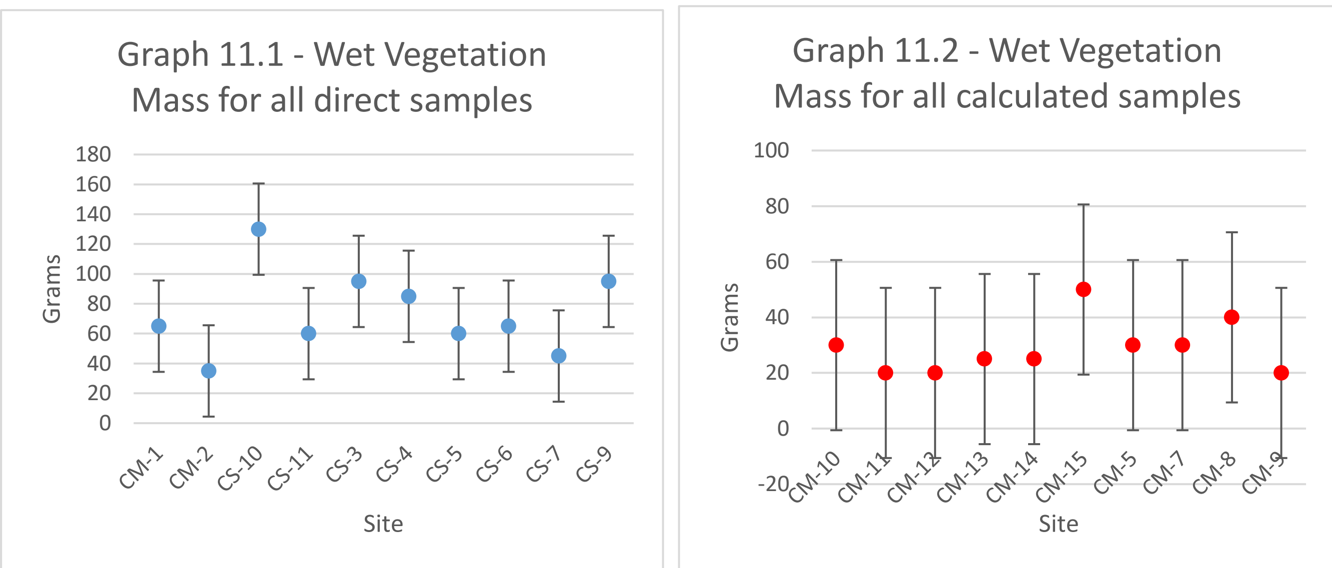


Figure 11: Wet mass of samples taken; Graph 11.1 represents the direct samples , and Graph 11.2 represents those samples calculated, error bars standard deviation from mean (P=0.05% from mean), represent the error associated with each sample.

The linear regression undertaken to ascertain the dry weight of the calculated vegetation samples indicated a strong relationship between the dependent variable (wet mass) and the independent variable (dry mass). This is because the multiple R value is high (0.83) suggesting a strong correlation between the variables (Open University, unknown), and the R squared value (0.69) is a moderate to good fit suggesting some variation (Open University, Unknown), with the significance f value (0.002) significantly below 0.5. This suggests that the statistical model is good at predicting the dependent variable (Open University, Unknown), Table 4 below identifies the full statistical analysis.

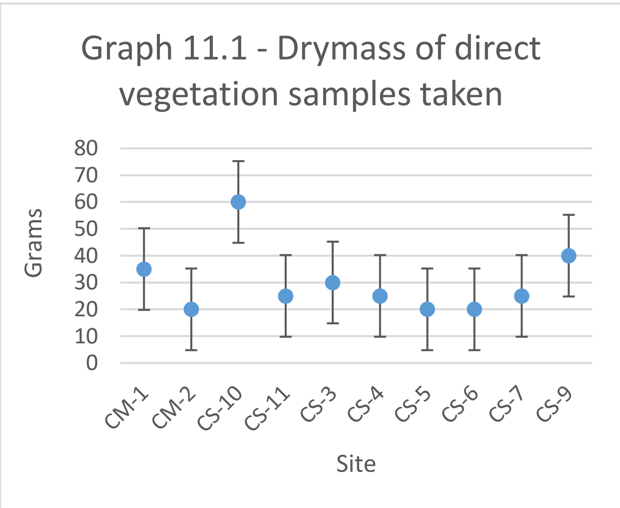
Table 4: Regression statistics and ANOVA for the linear regression used to convert wet mass into dry mass

Regression Statistics	
Multiple R	0.835399
R Square	0.697891
Adjusted R Square	0.660127
Standard Error	16.31956
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	4921.875	4921.875	18.48049	0.00262
Residual	8	2130.625	266.3281		
Total	9	7052.5			

Figure 12 includes the calculated results for all the vegetation dry mass, which produces an average of 18.20 grams per cm^3, with a standard deviation of 15.22 grams per cm^3. This high standard deviation was due to the small wet weight used to calculate the dry mass, when compared to the direct sampled sites, see Figure 11 above.



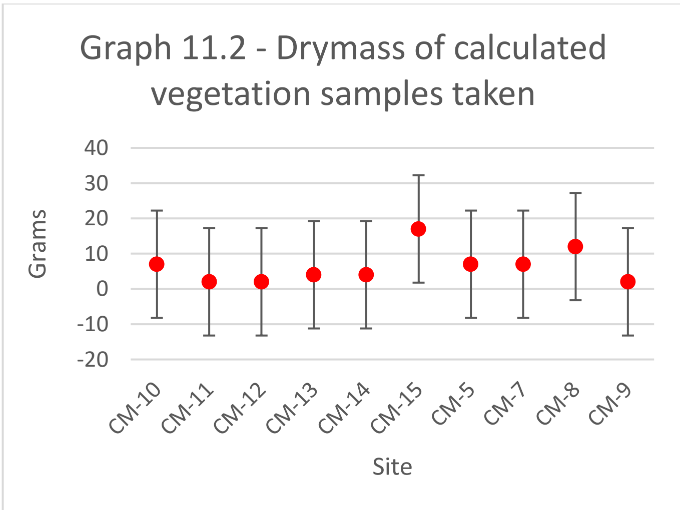


Figure 12: The dry mass of all samples taken; Graph 12.1 represents the direct samples; Graph 12.2 represents calculated samples; error bars = standard deviation away from the mean (P=0.05% from mean), and represents the errors associated with collecting the sample.

4.2.3 Carbon Released from Vegetation

From undertaking the calculation identified in Equation 3 it was possible to determine that on average 237.55 tonnes of carbon was released, see Figure 13 below, based upon the average figures used for each aspect identified above. The maximum (799.13 tonnes) and the minimum (25.57 tonnes) was also calculated which provided a range of 773.56 tonnes depending upon the figures used.

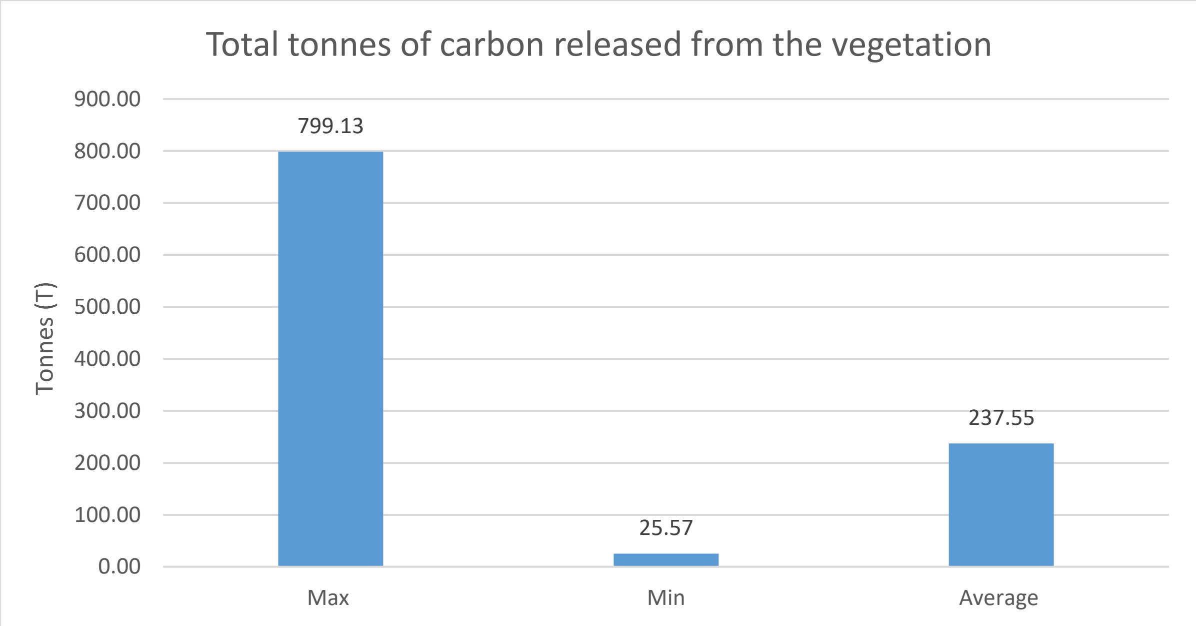


Figure 13 total carbon released from the vegetation component of the ecosystem

4.3 Total Carbon Released to the Atmosphere

Taking into account the amount of carbon that was converted into black carbon, on average 11,946.74 tonnes of carbon (see Table 5 below) was released into the atmosphere from both vegetation and soil combined. Although this figure could be as high as 32,596.72 tonnes or as low as 4,152.71 tonnes.

Table 5: Total carbon released to the atmosphere

	Max	**Min**	**Average**
Total Tonnes (T) carbon released to the atmosphere from soil	31,828.96	4,128.24	11,719.40
Total Tonnes (T) carbon released to the atmosphere from vegetation	764.77	24.47	227.34
Total Tonnes (T) carbon released into the atmosphere combined	32,593.72	4,152.71	11,946.74

4.4 Carbon Dioxide Released to the Atmosphere

Using the average figures for the total carbon released to the atmosphere from both vegetation and soil, it is estimated that 43,844.53tonnes of carbon dioxide was released into the atmosphere as a result of the wildfire (see Table 6 below). Due to the variability of the different factors involved in calculating the figure, a minimum and maximum amount of carbon released was also calculated (15,240.45 and 119,618.96 tonnes respectively).

Table 6: Tonnes of carbon dioxide (CO_2) released from soil and vegetation as a result of the wildfire

	Max	Min	Average
Total Tonnes (T) carbon dioxide released to the atmosphere from soil and vegetation	119,618.96	15,240.45	43,844.53

4.5 Comparison to Roaches summer wildfire

In August 2018 a wildfire occurred on the Roaches in the South-West Peak (*Titterton et al 2019a*). MFFP has a monitoring site located within the burn scar of this fire too, collecting the same data as the monitoring site on Marsden. The Roaches wildfire took place in summer and the Marsden wildfire took place in spring.

The amount of carbon released during the Roaches wildfire was estimated and is compared to the results from the Marsden wildfire in Table 7 and Table 8 Comparing the average figures, there were 11,719.40 tonnes of carbon released to the atmosphere on Marsden and 3,114.67 tonnes from the Roaches. When comparing the tonnes of carbon released to the atmosphere per hectare, on average the Roaches released 50.5 tonnes per hectare and Marsden released 17.6 tonnes per hectare.

Table 7: Total Tonnes (T) carbon released to the atmosphere from soil, for both the Roaches and Marsden wildfires

	Max	Min	Average	Hectares
Marsden	31,828.96	4,128.24	11,719.40	665.94
Roaches	13,999.48	1,447.06	3,114.67	61.7

Table 8: Total Tonnes (T) carbon released to the atmosphere from soil per hectare, for both the Roaches and Marsden wildfires

	Max	Min	Average
Marsden	47.8	6.2	17.6
Roaches	226.9	23.5	50.5

5. Discussion

This research looked at the quantity of carbon released from an area of blanket bog following a wildfire. It demonstrates that approximately 11,946.74 tonnes of carbon was released into the atmosphere (excluding pyrogenic carbon), of which, 11,719.40 tonnes of carbon came from the peat and 227.3 tonnes of carbon came from the above ground vegetation.

Comparison between carbon loss from vegetation and soil

This suggests that approximately 98% of the total carbon loss comes from the peat, despite the small depth of peat lost because of the wildfire. This is consistent with the existing literature, which identifies the important role of peat as a carbon store (*Davies et al, 2013*).

Despite this difference, it is important to recognise the role that vegetation plays in retaining carbon within the environment. This is because it not only acts as a carbon store itself, but also can have implications for ongoing carbon loss through erosion of the peat and black char that develops on a site *(Clay and Worrall, 2011).*

Using the 'average' value

Furthermore, this study may underestimate the amount of carbon produced as the peat depth sample locations were situated within a 'low severity' burn area. It is therefore possible that the average figure of carbon loss (11,946.74 tonnes) is a conservative estimate and it may be closer to the maximum (32,593.72 tonnes) figure. The majority of the burn scar was recorded as 'low severity' (66.8%) but a large proportion was either 'moderate-low' or 'moderate-high' (27.7%) which would suggest the damage and therefore carbon loss in these areas would have been higher. As noted by Warren *et al* (*2012*) this figure can only be an estimate as all the factors (e.g. soil bulk density etc.) will vary across the site and it is beyond the scope of the study to identify these variations across the whole site.

Comparison to other studies

Comparing the bulk density of peat soils to the study undertaken by Crouch and Chandler (*2021*) in the Bamford catchment, it suggests that this study's results are in keeping with what is found in the wider literature. Crouch and Chandler (*2021*) found an average bulk density of 0.25g cm^3 and a maximum of 0.318g cm^3 . Whilst this study's figure of 0.30g cm^3 is close to the maximum this could be due to the fact that we only sampled the top 5cm, whereas Crouch and Chandler sampled the top 15cm. This is in keeping with the findings that the higher up in the peat profile you go, the denser the peat gets (*Crouch and Chandler, 2021*).

The average figure for carbon released from the peat as a result of the wildfire is 11,719.40 tonnes, which is the equivalent of 17.6 tonnes per hectare. The Marsden fire took place in spring, covering a large area (665.94 ha) but the peat loss was small (1.56 cm). The fire that occurred in the Roaches in summer 2018 occurred in a smaller area (61.7 ha) but the peat loss was much larger (5.3cm) (*Titterton et al 2019a*). The Roaches fire released 3,114.67 tonnes of carbon, which is the equivalent of 50.5 tonnes per hectare. Therefore, the Marsden fire released more carbon because the area affected was much larger, but the severity of the Roaches fire was much greater and caused more peat loss. This difference could be further exaggerated as the Roaches figure could be an under estimation, as the location of the peat anchors on the Roaches was situated in a bowl, making the ground wetter and therefore less susceptible to the impacts of fire when compared to the other areas of the site.

The amount of carbon released from the peat on Marsden (17.6 t C ha-1) is within the value range (minimum 2 t C ha-1 and maximum 110 t C ha^{-1}) in Poulter *et al* (*2006*) study, which examines smouldering wildfires in temperate peatlands of America. It is also within the range of the figures calculated for Boreal peatlands (15 – 28 t C ha-1) of Canada *(Davies et al, 2013*. However, it is much lower than the 96 tonnes per hectare calculated by a similar study focussing on Scottish peatlands undertaken by Davies *et al* (2013), which is much closer geographically but on a heather dominated moor. The lack of comparable studies using actual before and after peat depth data highlights the difficulty in drawing accurate comparisons between this study and the wider literature.

The carbon released per hectare figure was also calculated for the vegetation component of the ecosystem which gives an average figure of 0.3 T – CO_2 per hectare which is in keeping with those figures summarised in the Lindsay *(2010)* review which identifies biomass-carbon values for non-forest vegetation types as being uniformly very low, ranging from 0–2 t C ha-1. Additionally the average carbon content of plants (49.5%) is in line with what is found within the literature with a min of 41.3% and a max of 50.4 depending on the type and part of the plant sampled *(Suhui Ma, 2018).*

There are a number of reasons for differences in burn severity including site variation in fuel type and fuel structure as well as by differences in fire weather conditions *(Davies et al, 2016).* This is seen in the Marsden fire as those areas that was mapped as moderately high severity areas almost directly corresponded to locations where *Calluna Vulgaris* (heather) was present. This is what we would expect to find as heather has been shown to burn at hotter temperatures (*Gingham, 1972*) than grass, which has the potential to create a more severe wildfire burn.

The vegetation type however does not explain the other levels of burn severity, as the other burn severity levels do not correspond to other vegetation types. It was also reported that the Marsden fire spread very quickly due to the wind speed and direction, which is what would be expected from a grassland fire (*New South Wales, 2010*). The dominant vegetation on the site may also explain why the wildfire on the Roaches was much more severe than the one that happened in Marsden, as the Roaches site contained a lot more heather than the Marsden site.

Potential impact of vegetation type

The vegetation was sampled around the perimeter of the burn scar as this more accurately reflects what the vegetation was like prior to the wildfire as the area is likely to be comprised of vegetation that is quick growing (e.g. *Molinia caerulea and Chamerion angustifolium*). Although no formal vegetation survey was undertaken, it was noted that the quadrats primarily contained grassland species including *Molinia caerulea, Eriophorum angustifolium, Eriophorum vaginatum* and *Polytrichum*. This is in keeping with those species identified from the formal vegetation surveys undertaken as part of MFFP's Community science monitoring site that was located within the burn area, suggesting that the vegetation was a good match for what was there previously.

Context of the amount of carbon dioxide released

Taking into account the amount of pyrogenic material left behind as a result of this wildfire, the average amount of carbon released to the atmosphere is 11,946.74 tonnes, which when converted into carbon dioxide is 43,844.53 tonnes. A comparison to the MoorLIFE 2020 project identifies that approximately 224.8 times more carbon was released in this one event than the 195.04 tonnes of carbon dioxide released in the whole fourth year of MoorLIFE 2020. The fourth year of MoorLIFE 2020 delivered 2,776ha of gully blocking, planted 846ha of *Sphagnum* moss plugs, flown and spread 6,761 bags of brash, controlled 1,414.8ha of invasive species and re-vegetated 33.1ha of moorland, and included over 400,000km of travel. This amount of carbon released from the fourth year of MoorLIFE2020 is the equivalent to running 4,834 homes for one year.

The work undertaken by Worrall *et al* (*2011*) indicates that the bare peat restoration work MFFP undertakes protects 4.48 tonnes of carbon per hectare per year. Therefore, it would take 3.93 years to protect the same amount of carbon released in this wildfire. This emphasises the importance of the work that MFFP does, helping to re-wet moorlands and by communicating the importance of reducing wildfires.

Not only did this wildfire release carbon into the atmosphere it also affected the restoration work undertaken as part of the MoorLIFE 2020 project. This includes loss of *Sphagnum* moss plugs that had recently been planted and a monetary loss to reinstate the bare peat restoration and gully blocks that were destroyed in the fire. Furthermore, Clay and Worrall (*2013*) identify that wildfires can reduce the build-up of litter in the humus layer, as the vegetation is lost to the habitat. This can have implications both in terms of NPK nutrients (*Bragazza et al, 2008*) being released into the peat and the build-up of peat, especially where *Sphagnum* moss is concerned further reducing the moors ability to retain carbon as well as taking a longer time to recover to a favourable condition as defined by Natural England.

6. Summary

This study investigated carbon loss on Marsden. Key findings were:

- 11,946.74 tC (43,844.53 tCO_2) released from Marsden fire.
- There is a significant difference in the amount of carbon released when compared with emissions from large project such as ML2020.
- It will take approximately 3.93 years of avoided carbon loss to recover the same amount of carbon material lost from the peat.
- A summer fire on the Roaches resulted in the loss of more carbon than the spring fire in Marsden per hectare, but the spring fire released more carbon as it affected a larger area.

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