Ricardo
Energy & Environment

Carbon loss and economic impacts of a peatland wildfire
in north-east Sutherland, Scotland, 12-17 May 2019
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Report for WWF-UK

ED 12990 | Issue Number 3 | Date 11/11/2019

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WWF-UK

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11 November 2019

Ricardo Energy & Environment reference:

Ref: ED12990- Issue Number 3

Executive summary

On 12 May 2019 a wildfire started in north-east Sutherland, Scotland, UK, and burned for almost six days. Based on remotely sensed data, the estimated wildfire area, excluding open water, was 54.9 km^2. This wildfire area was dominated by blanket bog (53.8 km^2).

In this study there has been no assessment of burn severity, and no site visit. We have anecdotal reports that the fire was fast and light across much of the burned area, and that recovery of flora was occurring within a few weeks of the fire. We present potential carbon loss values across a range of possible scenarios reflecting different fire severities.

From a range of published studies of carbon loss to atmosphere during a wildfire on peat bog, the mean of reported mid-range carbon loss values was 290 kt, with reported mid-range values ranging from 124 kt to 928 kt. Using Intergovernmental Panel on Climate Change (IPCC) methods, the comparable mid-range carbon loss value was 230 kt with a smaller range of 174 kt to 294 kt. This was for a scenario that assumed 20% of the burned area had been drained.

Reported values of carbon loss include values, scaled up to an area equivalent to the area of the north Sutherland wildfire, varying from 20 kt to 933 kt. The north Sutherland wildfire is understood to have been of low severity across much of the burned area, suggesting that carbon loss may have been at the low end of this range, but that there is potential for much greater losses in the event of a more severe fire on blanket bog.

The IPCC default values for organic soil fuel consumption show a large difference in values between drained and undrained peat, contributing to peer-reviewed evidence for loss of carbon from wildfires on drained peat bogs being five to nine times greater than loss of carbon from wildfires on undrained peat bogs.

To give some context to the estimated carbon loss values using IPCC methods, the low carbon loss value for the 20% drained scenario, of 174 kt is equivalent to 1.7% of the total greenhouse gas emissions for Scotland in 2017, equivalent to approximately 6.2 days of 2017 daily average greenhouse gas emissions in Scotland.

There was close agreement in carbon loss values estimated from published reports of previous wildfires on peat bog, and carbon loss values from the Tier 1 IPCC method for emissions from fires on drained inland organic soils given in IPCC (2014). Values using data from reports of other fires had a mid-point of 290 kt C, compared with values of 204-256 kt C (mid-range values, but varying depending on the scenario for percentage of the area that was drained) using the IPCC method.

Generally, for peatland fires that are carbon sinks, where peatland is burned severely leaving bare peat, restoration can return the ecosystem to a carbon sink more quickly than for natural regeneration through avoided loss of carbon and carbon sequestration. Restoration of severely burned peatland is cost neutral up to a cost of £3,460 ha capital investment when assuming a £220 per ha annual cost.

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1   Background

On 12 May 2019 a wildfire started in north-east Sutherland, Scotland, UK, and burned for almost six days (BBC News, 2019). The press reported that "More than 20,000 acres (8,093 ha) of peatland, including 1,482 acres (600 ha) at Forsinard Flows [the RSPB reserve, Forsinard Flows] were burned" (BBC News, 2019). The burned area is predominantly blanket peat bog and includes land that has been forested and land that was being restored to peat bog by removal of trees and reversal of drainage.

Consequences of this wildfire include loss of organic carbon stored in vegetation and peat, emitted to the atmosphere by combustion to carbon dioxide, and economic impacts through damage to natural capital. This report presents high-level assessments of the impact of this wildfire on released carbon from the peatland and the natural capital damage to the area. The assessment is based on carbon loss values presented for other peatland wildfires, and calculations using peer-reviewed methodology from the Intergovernmental Panel on Climate Change (IPCC).

2 Project objectives

The project objectives were:

- To estimate carbon loss to atmosphere from combustion,
- To estimate the economic value of the natural capital damage.

3 Methods

3.1 Carbon loss calculations

We made estimates of the carbon loss to atmosphere using:

- data on the area burned,
- estimates of carbon loss made for other wildfires on peat bog in similar climates,
- Intergovernmental Panel on Climate Change (IPCC) guidance on greenhouse gas (GHG) emissions from wildfires.

Estimates are presented as a range that we would expect the carbon loss to fall within.

The burn area was identified using analysis of remotely sensed data[1] taken from the European Space Agency's (ESA) Sentinel 2 satellite. Cloud free images were required in order to understand the pre-burn land cover type and the extent of the post-burn area and land cover when the fire was extinguished. The required datasets were identified using the EO Browser (Sentinel Hub, 2019), with the 12 March 2019 being selected as the pre-burn land cover, and two sets of images, 16 May 2019 and 15 July 2019, were identified for the post-burn extent and land cover. All three datasets were downloaded from the ESA Copernicus Open Access Hub (Copernicus Open Access Hub, 2019).

Each Sentinel 2 data set contains a number of individual spectral bands. For the purposes of these analyses spectral bands 2 (blue), 3 (green), 4 (red) and 8 (near infrared) were used. For each of the three dated datasets the individual bands were clipped to the study area and an Object Based Image Assessment was performed on the images using SAGA GIS (System for Automated Geoscientific Analyses, 2019) and QGIS (QGIS, 2019). This technique groups the images together into similar pixel areas which represent similar land cover spectral reflectance values. A selection of these pixel areas

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[1] Copernicus Sentinel data 2019, processed by ESA.

was assigned a land cover type (which were identified using true colour and false colour satellite images made from the four individual bands) to create a training dataset. For these images several individual land cover types were used; 1) freshwater (including open water, bog, marsh and pools of water), 2) seawater, 3) woodland, 4) grassland (including pasture and scrub), 5) upland vegetation, 7) cloud, 8) shadow and 9) burnt area. The resulting training dataset was used by SAGA GIS to classify each of the individual pixel area groups into one of the nine land cover types. This produced classified land cover data for the 12 March, 16 May and 15 July 2019. The classified land cover data were checked against true colour and false colour images as well as extant aerial imagery to ensure that the assigned land cover types were realistic.

Using the classified land cover data, the burn extent was then defined. It should be noted that the post-burn extent and land cover required two datasets to create. The 16 May 2019 image showed the majority of the burn extent with most of the fire extinguished, however active fires were still burning at the northern margin of the fire near the coast. There were no new cloud free images of the northern margin of the burn area until 15th July 2019. The resulting classified land cover images on both dates were combined to produce a single burn extent and land cover dataset representing the land surface after the fire had been extinguished.

The burn extent was overlain on the 12th March classified land cover data to enable calculation of the areas of land cover present within the burn area prior to the fire. The single burn extent and land cover data representing the post-burn conditions was also processed to calculate the area of land cover types after the fire had been extinguished. The difference between these pre and post areas provided an understanding of the area of land cover lost due to the fire.

In this study there has been no assessment of burn severity, and no site visits. We have anecdotal reports that the fire was fast and light across much of the burned area, and that recovery of flora was occurring within a few weeks of the fire, but that there were also some areas that were burned more severely. Our analysis makes no attempt to estimate the effect of burn severity on carbon loss in the north Sutherland wildfire, but we present a range of values indicating the potential for carbon loss across a range of possible scenarios reflecting different fire severities.

3.2 Economic appraisal

An economic appraisal measures "welfare", a combination of wellbeing and utility, and not only money income, but also total economic value[2]. Our analysis is based on a "societal" point of view (to account for a public sector perspective) using the ecosystem services approach. Where possible, we have monetised impacts, expressed in consistent units for aggregation, based on a unit of change taken from official sources, historic evidence or academic literature. This approach allows us to look at the highest net benefit, accounting for the social welfare rather than the commercial gain[3].

An economic appraisal of the damage to the burned area is linked to the estimate of carbon loss, because the loss of carbon to the atmosphere contributes to climate change which has economic consequences.

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[2] We did not carry out a financial estimate, as these are related to the financial costs and benefits that can be exchanged in a market using money.

[3] This approach is widely used and recommended by official sources such as "How to Apply an Ecosystem Approach," Scottish Natural Heritage, accessed June 13, 2019, https://www.nature.scot/scotlands-biodiversity/ecosystem-approach/how-apply-ecosystem-approach; "Scottish Natural Capital - Office for National Statistics," accessed June 13, 2019, https://www.ons.gov.uk/economy/nationalaccounts/uksectoraccounts/bulletins/scottishnaturalcapital/ecosystemserviceaccounts2019; "Scottish Natural Capital: Ecosystem Service Accounts 2019 - Gov.Scot," accessed June 13, 2019, https://www.gov.scot/publications/scottish-natural-capital-ecosystem-service-accounts-2019/pages/10/.

3.2.1 Economic appraisal steps

To assess the economic damage of the fire, we estimate the direct costs of the fire, the indirect post-fire costs for 15 years, and the benefits to society for restoring the peatland.

1. Estimate baseline costs of the fire from the carbon losses, firefighting cost, and other costs if relevant and quantifiable.

To estimate the baseline costs, each tonne of carbon lost during the fire is valued first. Given the remoteness of the area, the cost category that is expected to dwarf all others is the social cost of the carbon emitted. This is defined as the *"cost to global economic damages associated with a one-ton increase in CO_2 emissions in a given year"*, which is adapted from the Scottish government's annual accounts of ecosystem services, which uses the average non-traded UK carbon price (£68 in 2019). This category also includes a valuation of the costs of firefighting.

2. Estimate quantifiable costs to society of having a large burned peatland, in terms of the losses to human welfare (utility), multiple years after the fire (modelling is done up to 15 years after the fire).

To estimate the further costs to society after the fire, the economic appraisal valued what is lost by having a burn scar, and the continued costs from both lost carbon sequestration, and additional carbon lost in the period after the fire. It is understood from literature that burn scars can remain a net source of carbon for more than a decade (Weider et al. 2009), although in the case of the north Sutherland wildfire the fire was not severe across much of the burned area and vegetation recovery has started rapidly. The analysis therefore shows the potential for costs to society from a fire of this size with a fire sufficiently severe to remove the flora. This will be most applicable to those areas to the north of the burned area that had the most severe burn damage.

The analysis further includes loss of welfare to Scottish residents, as a result of loss of biodiversity, vegetation, and related recreational and existence values. As these values are difficult to quantify, we use literature on the willingness-to-pay (WTP) of Scottish citizens in a stated preference study done in Scotland in 2018. This study uses choice experiments to ascertain the level of income that Scottish residents are prepared to lose to see bare peatland restored to good condition, which implicitly includes a valuation of carbon emissions (#1), water quality (#2) and wildlife (#3) from poor (bare soil, including burned land), to intermediate (drained), to good (wetted, pristine or restored) condition (Glenk and Martin-Ortega, 2018). To use the data for this study, the valuation is also done over 15 years.

3. Estimate benefits of restoration, in terms of carbon emissions saved, and other ways the peatland provides value to society.

Following the stated preference study from Glenk and Martin-Ortega (2018), an estimate is made on the benefits of restoring a burned area to its pre-fire condition (intermediate and good), in terms of

- The value to Scottish society of having peatland restored (from the willingness to pay),
- The value to global society of reducing/preventing carbon emissions (from the social cost of carbon) from an unrestored burn scar.

These two costs overlap in their valuation of carbon emissions. The UK non-traded carbon price already includes a social valuation of the damages of climate change. Therefore, the stated preference value should be reduced to avoid double counting of the carbon benefits. There is no quantitative estimate of the share that carbon sequestration has in the willingness to pay estimates. From the Glenk and Martin-Ortega (2018) study design, the WTP of citizens for restoring land from poor to good included a heavy focus on the fact that a 'good' condition sequesters carbon. A conservative estimate is used here that assumes 25% of the valuation for restoration by citizens,

through their knowledge that it will sequester carbon. This means we will reduce the benefits associated with restoration from the WTP estimates by 25%.

Again, in the case of the north Sutherland wildfire the fire was not severe across much of the burned area so restoration may not be required except in areas that had a more severe fire. As we have not assessed the severity of the fire, the analysis provides an indicative estimate of restoration benefits in the event of a fire sufficiently severe to remove the flora.

3.2.2 Discounting

A social time preference of 3.5% is used, according to UK Government guidance. This includes the 'time preference', including the preference of value now rather than later, and the 'wealth effect', reflecting expected per capita growth, where future consumption is then higher and expected to have a lower utility. The baseline data sources for our appraisal (Glenk and Martin-Ortega, 2018 and the Scottish Natural Capital accounts) also use this discount rate, so that their data and conclusions are directly applicable.

4 Carbon loss impacts

4.1 Wildfire area and land characteristics

The estimated pre- and post-burn land cover areas, based on remotely sensed data, are presented in Table 4-1. The data show a total area for the wildfire of 56.1 km^2, including 1.2 km^2 of open water. This leaves a burnt area of 54.9 km^2, excluding open water within the wildfire area. Of this area, 53.0 km^2 were identified as burnt. This burnt area was dominated by 'bog, marsh, pools of water and upland vegetation', which is blanket bog.

As a caveat to the data presented in Table 4-1, we understand from local observations that the wildfire progressed into forest and burned only the under storey, and therefore these burned area of forest are unlikely to be detected from remotely sensed data. The area of forest burned and also the total area burned, therefore may be underestimates, but the extent of underestimation cannot be confirmed within the scope of this study, which has not included any site visits. We have used the potentially under-estimated area value, but noting that, in this respect, our estimates of carbon loss take a conservative approach.

Table 4-1. Pre and post burn land cover areas.

Land cover	Pre-burn areas (km²)	Post-burn areas (km²)	Loss (km²)
Bog, marsh, pools of water and upland vegetation	53.809	1.688	52.121 See note a
Grassland, pasture and scrub	0.258	0	0.258
Open water	1.228	1.169	See note b.
Woodland	0.797	0.204	0.593
Burnt area	-	53.035	Not applicable
Total area (see note c)	56.093	56.097	Not applicable
Total area excluding open water	54.865	54.928	Not applicable

NOTES:

a. Bog, marsh and pools of water are discrete pools of water which are commonly grouped together. They were not identified on the burnt area images due to having a similar spectral response to the burnt areas. However, they are visible in post-burn images and so have not been lost during the fire.

b. Open water classification shows a slight reduction in area. This is likely due to classification variability and is unlikely to be a loss of open water.

c. There is a slight mismatch in total areas, this is to be expected from land cover classification using satellite imagery.

We understand from local sources that the burnt area included:

- Undrained peat;
- Drained peat (some associated with forestry, some for improved grazing);
- Drained peat that is being restored (not previously forested);
- Drained peat that is being restored (previously forested);
- Forestry with understorey fire (not clear from satellite imagery);
- Areas of shallow peat on slopes, near burns.

We also understand from local contacts that there were no habitations within the burnt area. The land is used for the following purposes:

- deer stalking,
- fishing,
- shooting,
- wildlife watching,
- scientific studies,
- conservation and restoration activities.

Approximately 600 ha (6 km²) was land managed by the RSPB as part of the Forsinard Flows RSPB reserve.

4.2 Carbon loss estimates based on studies of previous fires

Searches for reports of previous fires focussed on peatland fires in Scotland and boreal sites in Europe and north America. We identified 18 reports with potentially useful data or descriptive information, for more detailed review. Of these, eight papers included quantified estimates of carbon loss from peat burning during wildfires (Table 4-2). Most data reported from these papers are from sites with forest or scrub cover. Most studies included carbon loss from combustion of vegetation, litter and peat, but this is not clearly stated in all studies.

The data show a wide range of values, from 0.37 to 85 kg C m^{-2} lost from peat combustion at the time of a wildfire. To obtain data for estimating carbon loss from the north Sutherland fire, we excluded data from two of the studies in Table 4-2:

- Davidson et al., 2019 (the values of 10 – 85 kg C m^{-2} were not supported by any context and the upper value is an outlier);
- Reddy et al., 2015 (the values of 0.92 – 44 kg C m^{-2} were obtained with contrasting, experimental methods and the upper value is an outlier).

From the remaining data in Table 4-2, we took a mid-point from each range and then took the minimum, mean, and maximum values from the 11 range mid-points. These were then used with the area estimate (see 4.1) to calculate potential total carbon loss and CO_2 emission, for the north Sutherland fire (Table 4-3). Because of the small number of literature reports, and high uncertainty about the similarity of wildfire characteristics between reported studies and the north Sutherland fire, we provide descriptive statistics only.

To give some context to the emissions in Table 4-3, the mean mid-range carbon loss value of 290 kt is equivalent to 2.8% of the total greenhouse gas emissions for Scotland in 2017[4].

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[4] Based on a total C equivalent emission for Scotland in 2017, of 10,244 kt, from the latest Devolved Administration report by the NAEI: Greenhouse Gas Inventories for England, Scotland, Wales & Northern Ireland: 1990-2017. https://naei.beis.gov.uk/reports/reports?report_id=991

Table 4-2. Carbon loss values (kg C m⁻²) from published reports of losses at peatland sites.

Carbon loss (kg C m⁻²)	Location and other notes	Reference
2.0 ± 0.5 16.8 ± 0.2	Forest site in Alberta, Canada Undrained Drained	Turetsky et al., 2011
10 – 85	Data not found in Turetsky et al., 2011.	Davidson et al., 2019, citing Turetsky et al., 2011
2.51 – 9.35	Dense shrub-scrub and pine woodland vegetation in North Carolina, USA. Averages for burn depths of 0.01 m and 0.10 m.	Poulter et al., 2006
9.6 ± 1.5	Scotland, forest site, smouldered for a month after the fire began.	Davies et al., 2013
0.37 – 2.97 1.45 – 2.97	Russia, forest site Measurements in this study Other authors (sources not given)	Glukhova and Sirin, 2017
0.92 – 44	Forest site, Great Dismal Swamp National Wildlife Refuge, VA, USA. Range reflects alternative assessment methods: low value from a modelling approach, high value using LiDAR to measure change in elevation.	Reddy et al., 2015
2.2 ± 0.5 2.5 – 3.0 1.3 – 3.9 4.9	Forested sites in N America. Cited by Turetsky and Wieder, 2001 Cited by Turetsky and Wieder, 2001 Cited by Turetsky and Wieder, 2001	Turetsky and Wieder, 2001 (Kasischke et al. 1995) (de Groot and Alexander 1986) (Zoltai et al. 1998)
2.5	Eastern Finland. Value is a mean determined by study of peat cores with charcoal layers.	Pitkänen et al. 1999

Table 4-3. Estimates of carbon loss and CO₂ emission from an area equivalent to the north-Sutherland wildfire area, using range mid-point values from literature reports of other wildfires.

	C loss ($kg\ C\ m^{-2}$)	C loss scaled up to the area of the north Sutherland wildfire (kt C)	CO_2 emission scaled up to the area of the north Sutherland wildfire ($Mt\ CO_2$)
Minimum mid-range value	2.3	124	0.5
Mean mid-range value	5.3	290	1.1
Maximum mid-range value	16.9	928	3.4

4.3 Post-fire carbon balance

In addition to the emissions directly from a fire, there may be further, and ongoing carbon loss after a fire, and loss of carbon sequestration that otherwise would have been expected. Here we provide some comment on this based on reported studies, but we are unable to estimate the post-fire losses for the north Sutherland wildfire: anecdotal information on the severity of the wildfire indicates that over large parts of the fire area there was a fast, light burn, burning the vegetation, but with only minor damage to the peat. Recovery has been rapid indicating that much of the flora survived the fire.

Weider et al. (2009) reported that, on a forested peat bog in Alberta, Canada, the bog remained a net carbon source for 13 years following a fire, and then switched back to a net carbon sink as recovery continued. It can be expected that the carbon dynamics will vary between sites and be different in bog ecosystems with and without trees, but we can expect that, in general after a wildfire, there will be a period before the flora has recovered sufficiently to return the bog to a net carbon sink. The length of this period will depend on the severity of the fire, and the extent to which vegetation has been killed.

Besides the emission of carbon after a fire, there is also a loss of sequestration that would have occurred if there had been no wildfire. Billett et al. (2010) report that accumulation rates in the UK range from -56 to -72 $g\ C\ m^{-2}\ yr^{-1}$ (based on measurements at two sites), with a historical range of -35 to -209 $g\ C\ m^{-2}\ yr^{-1}$.

Worrall et al. (2011a) studied the effect of revegetation on a site in the Bleaklow Plateau, Peak District, burned by a wildfire 4 years prior to measurements in 2003, assessing the effects of revegetation (restoration) on the carbon flux. The range of possible carbon gains from restoration of a burned site is estimated at 122 to 833 $g\ C\ m^{-2}\ yr^{-1}$ (based on 4 measurements across 2 years of the same burned peat). This includes the amount emitted by the unrestored, burned, bare soil (358 $g\ C\ m^{-2}\ yr^{-1}$) that is regarded as an 'avoided loss'. These estimates are from a site with erosion, and could be large over-estimates for the largely vegetated north Sutherland site, which does not have severe erosion.

Figure 4-1. Cumulative yearly CO₂ flux (CO₂ m⁻² yr⁻¹) from four restored (R) sites (including the average as R avg) and two unrestored sites with no vegetation, 4 years after burning (Worrall et al. 2011a).
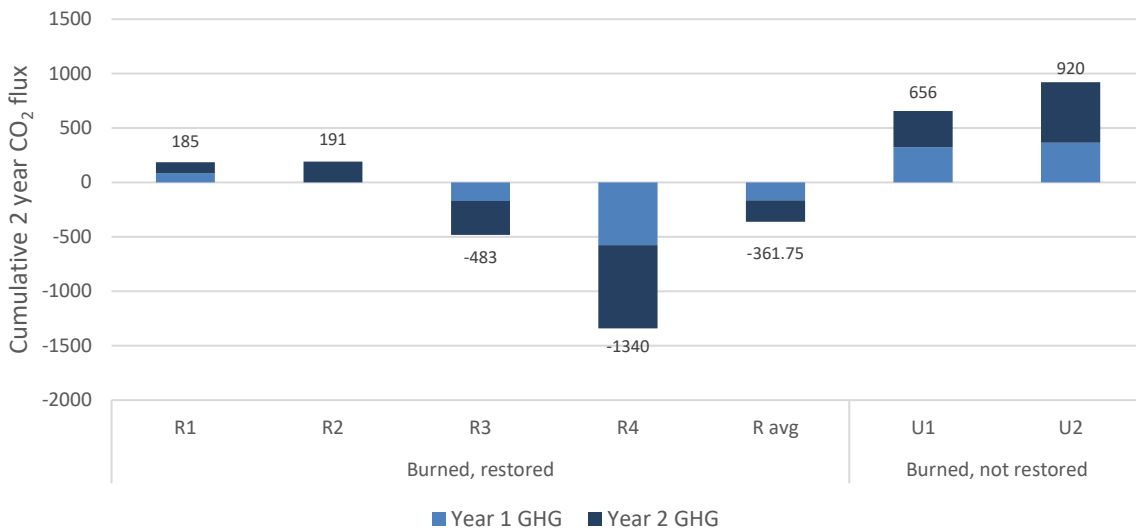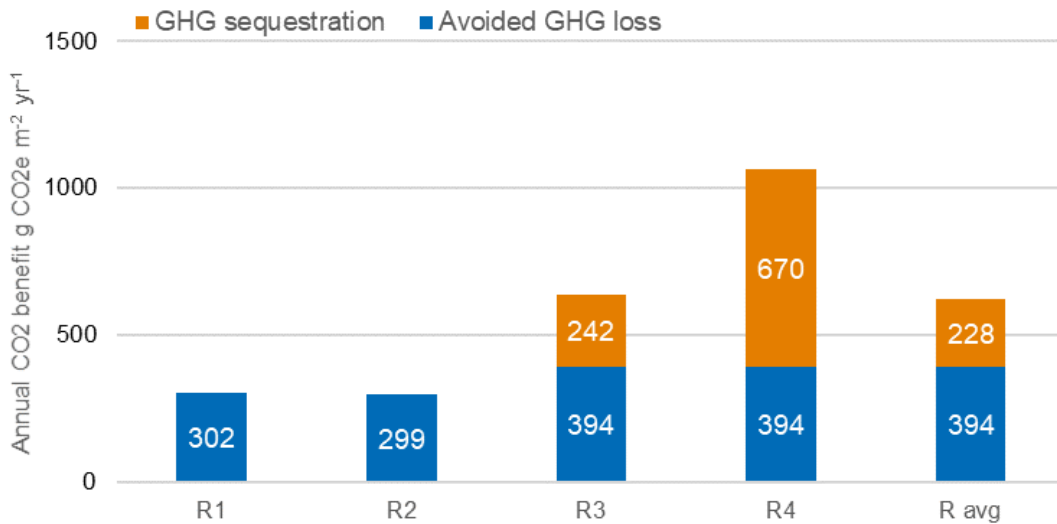

Figure 4-2. Estimated GHG benefits and avoided GHG losses from restoration of a burned site, measured 4 years after the fire and subsequent restoration (Worrall et al. 2011a). Maximum avoided GHG loss is the average of the measured unrestored sites, with any additional flux change recorded as a net GHG benefit.

There is a high variation in GHG benefits. Note that CO₂ flux is not the same as carbon flux. Principally, CO₂ flux is 44/12 = ~3.7 times bigger than the carbon flux, when all carbon is sourced or emitted as CO₂. There are however also other carbon sources and sinks, such as fluvial carbon (particulate organic carbon, dissolved organic carbon, dissolved CO₂ and CH₄) where carbon flows away from the site through water, and direct gaseous emissions of CH₄. Due to this, on average, in the Worrall 2011a study, only about 120% as much CO₂ is released directly through the peat surface

(in mass) compared with the carbon loss from the burned, unrestored sites. In the restored sites, there is no strong relationship between carbon and CO_2, especially at low carbon fluxes.

Figure 4-3 shows the relationship of the measured data in both years (there are four measurements for the controls, and eight for the restored sites). Highlighted in the figure are the measurements where there is a positive carbon flux (the system loses carbon) but still a net sequestration of GHG (positive climate effect). The author states this is because dissolved organic carbon and particulate organic carbon (DOC and POC) can be lost in great quantities from a burned site through water flows.

Figure 4-3. Relationship between carbon loss/sequestration and CO_2 flux measured at the surface (Worrall et al. 2011a). Highlighted is the situation where the system is losing carbon while sequestering CO_2 from the atmosphere.
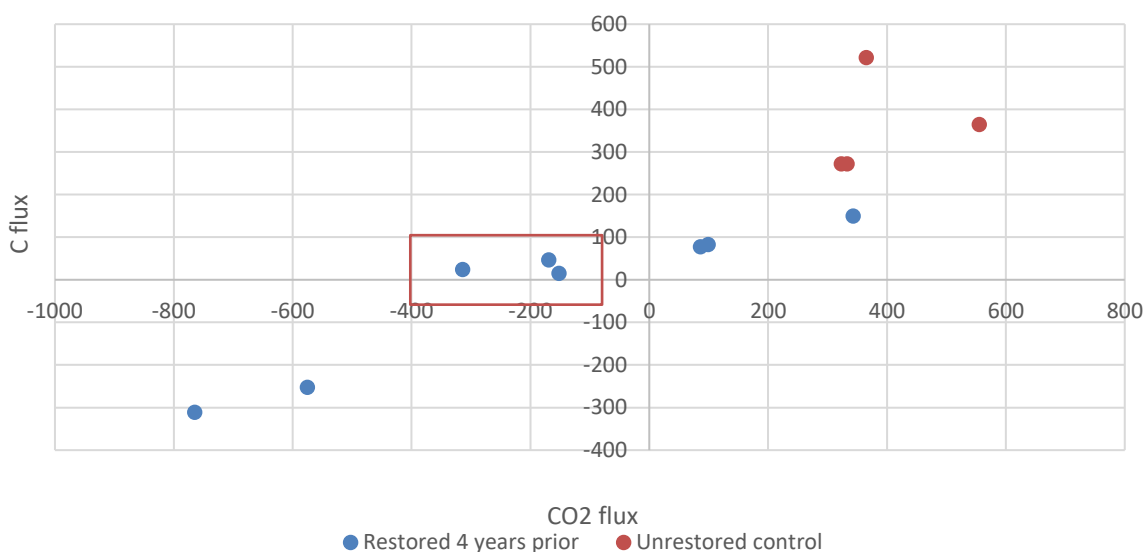
Comparing the data of carbon flux from the restored sites shows that there are still several processes ongoing (carbon loss through flow vs. high primary productivity capturing CO_2e). This would also explain the large variation between the four measurement sites in Figure 4-1. To provide context and better understand the benefits of a fully restored ecosystem that is accumulating carbon, Table 4-4 compares the average values of the restored and unrestored burn scar from the Worrall 2011a study to several other studies carried out on north Atlantic bogs. It shows that the equilibrium values of near-natural blanket bogs are generally comparable to the average measurement in Figure 4-1.

However, as the system is still under a net carbon loss in all of the restored sites, it is possible that some of the lost carbon through dissolved and particulate organic matter also ends up in the atmosphere, reducing the net sequestration significantly. Some studies have also been carried out with the assumption that all carbon lost to fluvial processes ends up in the atmosphere, resulting in these bogs being significant carbon sources. Furthermore, if the area is drained and under erosion, large amounts of carbon can also be lost through water flows, even in unburned sites (Pawson et al, 2008). Ultimately, how much of the lost carbon returns to the atmosphere is unclear, but it should be noted that only in a system where there is no net carbon loss can there be certainty that the system is a GHG sink.

Worrall et al. 2011b is a meta-analysis of many studies, and Table 4-4 shows literature on some peatland sites (though it should be noted that two are raised bogs, not blanket bogs).

Table 4-4. Literature on carbon loss/sequestration from bogs. Note that a negative value equals sequestration, a positive value is a loss.

Source	Location and state	CO_2e loss/sequestration (g CO_2e m^{-2} yr^{-1})
Worrall 2011a	North England: burned, restored 4 years after fire, 2006-2008	-181
Worrall 2011a	North England: burned, unrestored, 4 years after fire, 2006/2008	394
Worall 2009	Moor House England, blanket bog, 13 years since 1994	-216
Sottocornola 2005	Glencar, Ireland, pristine Atlantic blanket bog, 2003/2004	-202
Koehler 2010	Glencar, Ireland, pristine Atlantic blanket bog 2003-2008	-109
Roulet et al. 2007	Mer Bleue, Canada, ombrothropic continental raised bog, pristine, 1998 - 2000	-77
Nillsson et al. 2008	Degero Stormyr, Sweden, minerogenic oligotrophic raised mire, pristine, 2004	-86
Billet et al. 2004	Auchencorth Moss, transitional lowland raised bog, grazed, 1996	97
Dinsmore et al. 2010	Auchencorth Moss, transitional lowland raised bog, grazed, 2006/7	-352

From the data in the table, on average the CO_2e sequestration value for the post-wildfire, restored land is comparable to other blanket bogs across the UK and Ireland, and in the same order of magnitude as studies on some raised bogs.

The large difference between the unrestored (bare) post-wildfire site, the restored site, and other near-natural blanket bogs, shows there can be major gains to peatland restoration of a burn scar. Worrall et al. (2011b) summarises the different types of benefits of restoration:

1. Avoided loss of carbon from the burn scar, which it can be for decades if vegetation does not return and/or the area is not actively restored. The data in Figure 4-2 shows that this loss can be quickly remediated through restoration.

2. Transitional stage, where restoration or other management changes cause a change in the state of the peatland. For example, when bare peat regains a vegetation layer, this new vegetation represents a sink of CO_2.

3. Long-term sequestration from active, peat-forming peatland, over thousands of years.

4.4 Carbon loss estimates based on IPCC guidelines

The Intergovernmental Panel on Climate Change (IPCC) has published the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC, 2014). This document, often referred to as the 'Wetlands supplement', provides additional guidance on estimation of GHG emissions from wetlands, to supplement the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The coverage of the 2006 IPCC Guidelines on wetlands does not include peatland wildfires, but the Wetlands Supplement does include emissions from fires on drained inland organic soils.

As with other IPCC methodologies for estimation of GHG emissions, alternative methods are provided with differing levels of complexity. Usually there are three methods known as Tier 1, Tier 2 and Tier 3, with increasing complexity. Tier 1 is the basic method usually using default values for emission factors and some other variables if required; Tier 2 is intermediate, usually using country-specific emission factors; and Tier 3 is more complex, often bespoke, and with greater demands for activity data.

We have used the Tier 1 approach for emissions from fires on drained inland organic soils, to provide a check for the approximate magnitude of the emissions estimated using data from other reports of emissions from peatland wildfires (see Section 4.2).

We have used equation 2.8 from the Wetlands Supplement to estimate the emissions of carbon and methane from the north Sutherland wildfire. Equation 2.8 is as follows.

$$L_{fire} = A \bullet M_B \bullet C_f \bullet G_{ef} \bullet 10^{-3}$$

Where:

L$_{fire}$ = amount of CO_2 or non-CO_2 (e.g. CH_4) emissions from fire (tonnes)

A = total area burnt annually (ha)

M$_B$ = mass of fuel available for combustion (tonnes ha^{-1})

C$_f$ = combustion factor (dimensionless)

G$_{ef}$ = emission factor for each gas (g kg^{-1} dry matter burnt)

The value 10^{-3} converts L$_{fire}$ to tonnes

Default values are provided in the Wetlands Supplement for the product of M$_B$ and C$_f$, and for G$_{ef}$. For organic soil fuel consumption values, the product of M$_B$ and C$_f$, values are given for drained and undrained peat, with a large difference: mean values of 66 t ha^{-1} dry matter for undrained peat, and 336 t ha^{-1} dry matter for drained peat. Therefore, where a wildfire site includes drained and undrained areas (as is the case for the north Sutherland wildfire) it is highly important to obtain an estimate of the relative areas. In this case we do not have data for this, but we have made an estimate based on publicly available aerial photography: we overlaid the wildfire boundary and then marked areas within the wildfire boundary where drains can be seen. We also included areas of forest within the drained area, as we understand that these are usually drained. We did not include an area towards the north of the wildfire where there has been small-scale peat extraction for domestic burning over many years, as the scars from peat digging made it difficult to determine whether the bog is drained in these areas. The area identified as drained was approximately 10 km^2 (1003 ha), which is 18.9% of the burnt area. Recognising that our estimate of the drained area is conservative (because there may be drained areas not identifiable from aerial photography), we have generated three scenarios to illustrate the effect of the proportion of the area that is drained. The scenarios are:

1. 15% drained
2. 20% drained
3. 25% drained

The results of our calculations are given in Table 4-5 for each of the three scenarios. The range of values given reflects the range of values provided in the Wetlands Supplement for the product of M$_B$ and C$_f$, and for G$_{ef}$.

The results presented in Table 4-5 are in close agreement to the values in Table 4-3 from literature reports of other wildfires. Values using data from reports of other fires had a mid-point of 290 kt C, compared with values of 204-256 kt C (mid-range values, but varying depending on the scenario for percentage of the area that was drained) using the IPCC method.

The IPCC default values for organic soil fuel consumption and the large difference in values between drained and undrained peat, reflect the evidence for greater loss of carbon from wildfires on drained peat bogs, compared with undrained. The IPCC organic soil fuel dry matter consumption values of 66 t ha^{-1} for undrained peat, and 336 t ha^{-1} for drained peat, suggest that typically drainage increases carbon losses by a factor of five during a wildfire. Turetsky et al. (2011) reported that drainage increased carbon losses by a factor of nine during wildfire. It is, therefore, recognised in peer-reviewed studies, that drainage of peat bog greatly increases the risk of carbon loss during a wildfire. Therefore, restoration of drained areas could lead to significant C savings in the event of a fire by preventing catastrophic deep burning (Granath et al., 2016).

Table 4-5. Estimates of carbon loss (CO_2 carbon), methane (CH_4) emission, and carbon dioxide equivalent emissions (CO_2e, including global warming potential for CO_2-C and CH_4), from the north-Sutherland wildfire. These values were made using the Tier 1 method for emissions from fires on drained inland organic soils, in the IPCC Wetlands Supplement (IPCC, 2014).

Scenarios	Low	Mid-range	High
	CO_2 carbon (kT)		
15% drained	150	204	266
20% drained	174	230	294
25% drained	198	256	322
	Methane (CH_4) (kt)		
15% drained	2	5	9
20% drained	3	6	9
25% drained	3	6	10
	Carbon dioxide equivalent (CO_2e) (Mt)		
15% drained	0.6	0.9	1.2
20% drained	0.7	1.0	1.3
25% drained	0.8	1.1	1.4

To give some context to the emissions in Table 4-5, the mid-range carbon loss value for the 20% drained scenario, of 230 kt is equivalent to 2.25% of the total greenhouse gas emissions for Scotland in 2017[5], equivalent to approximately 8.2 days of 2017 daily average greenhouse gas emissions in Scotland. The low carbon loss value for the 20% drained scenario, of 174 kt is equivalent to 1.7% of the total greenhouse gas emissions for Scotland in 2017, equivalent to approximately 6.2 days of 2017 daily average greenhouse gas emissions in Scotland.

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[5] Based on a total C equivalent emission for Scotland in 2017, or 10,244 kt, from the latest Devolved Administration report by the NAEI: Greenhouse Gas Inventories for England, Scotland, Wales & Northern Ireland: 1990-2017. https://naei.beis.gov.uk/reports/reports?report_id=991

5 Economic impacts

The costs of a fire can be roughly divided into two categories:

- Direct costs from a fire,
- Indirect post-fire costs due to the changed landscape.

Direct changes in costs from the fire are given in Table 5-1.

Table 5-1. Potential direct costs from the north Sutherland fire, using the wildfire area (section 4.1) and carbon loss estimates based on IPCC guidelines (section 4.4).

Change in:	Economic impacts	Parameter	Cost per unit area	Total cost	Sources
GHG emissions	CO_2 damage costs	£ per tonne of CO_2	£68 (average damage) to £113 (95th pct damages) per t CO_2e	£48 m (average damage) to £79.8 m (95th pct damages)	IPCC method + social cost of carbon from Scottish ecosystem services
Human effort	Costs of fire fighting	£	Cost for a "large moorland fire"	1 to 5 million £	University of Manchester: Wildfire risk management case study
Biodiversity	Loss of natural capital from biodiversity	This cannot be directly estimated and is part of valuing the social benefits of restoration in 5.1.2.			
Air quality	Effect on human health from smoke plume	Not quantifiable		With the remoteness of the area with sparse population, there is no indication of notable impact on human health from smoke or water contamination.	
Water quality	Effect on human health from potential contaminated water	Not directly quantifiable			

Considering the social cost of carbon emissions, the potential direct costs from the fire in terms of carbon loss equate to about 48 million pounds. This is based on the 20% drained scenario, low estimate, of 174 kt C from Table 4-5. The low estimate was used, given evidence that the fire was not very severe across much of the burn area. This estimate goes to a larger value of nearly 80 million pounds in the scenario when applying 95th percentile damage costs. These high costs come from a climate change scenario where damages are in the 95th percentile of possible predictions.

Potential indirect changes in costs from the fire, on a per hectare basis, are given in Table 5-2.

Table 5-2. Indirect post-fire costs from the Sutherland fire, including potential peatland restoration.

Long-term cost category	Economic impacts	Parameter	Value	Sources
Continued GHG emissions and lost GHG sequestration	CO_2 damage costs	£ per tonne of $C(O_2)$	£68 - £112 2019 – 2034) to £113 - £173 (95th pct damages)	UK Government non-traded carbon price and Pindili et al. (2018) for 95th pct damages.
Other welfare benefits	Restored peatland wildlife	£ per ha, 15 year NPV	£3,842[6]	Glenk and Martin-Ortega (2018)
	Water quality			
Damage to local infrastructure	None expected			
Employment effects	None expected			

We have included peatland restoration, as the post-fire management choices made by the owners of the burnt area can have a big impact on the carbon emissions. As mentioned in 4.3, literature estimates (which are sparse) suggest that burned peat may continue to be a net carbon source for 10+ years. However, anecdotal information on the severity of the north Sutherland wildfire indicates that over large parts of the fire area there was a fast, light burn, burning the vegetation, but with only minor damage to the peat. Recovery has been rapid indicating that much of the flora survived the fire. In this situation, the possibility of restoration of bare peat by revegetation is limited to only small areas with severe damage from the fire. The extent of these severely damaged areas has not been assessed in this project, but it is assumed that the benefit from restoration will be small because of an assumed small area with severe damage. We are unable to estimate the costs or benefits of restoration for the fire area as a whole, so we provide only values per unit area.

From the range of values for the willingness to pay provided by Glenk and Martin-Ortega (2018), the value associated with a restoration from 'poor to good' condition, in a 'high peat concentration' area on non-wild lands is chosen. The willingness to pay for non-wild land is used as a conservative assumption, as significant areas of the burn area are either drained or used for peat extraction, to which point we can no longer assume that Scottish citizens would deem this area as wild. The base value of this benefit is equal to £2,900 capital investment and £220 annual costs per hectare of restored peatland from poor quality (e.g. barely vegetated after wildfire) over a 15-year period.

As mentioned in 3.2.1, the willingness to pay for peatland restoration by Scottish residents is used as a proxy for the societal benefits, minus 25% to account for the fact that this appraisal already accounts for the damages of emissions separately. With that in mind, the net present value (NPV) of restoring 1 ha of a burn area has been calculated. A restoration programme that has an initial investment cost of £3,460 per ha and an annual cost of £220 per ha returns all the investment as benefit to society and reduced GHG emissions. The higher value (£3,460 vs £2,900) associated with restoration vs. willingness to pay, is associated with the fact that our cost calculations include the social cost of carbon which include all damages to future generations. It is assumed that current generations, which took part in the stated preference study, do not fully value all the global costs of CO_2 in their valuations when asked about their willingness to pay for peatland restoration.

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[6] This value was estimated from Glenk and Martin-Ortega (2018), by taking the total estimated willingness to pay that would result in a net cost of 0 to society, for restoring 'poor' condition peatland to 'good' condition, predicting benefits to water quality, wildlife and carbon sequestration, for a peatland with a high concentration (>30%) of peat, in a non-wild land area. This includes £2,900 per ha capital investment for restoration, and £220 annual cost post-restoration for a duration of 15 years, discounted by 3.5%. This benefit is further reduced by 50% to avoid overlaps with the GHG valuation.

Glenk and Martin-Ortega (2018) cite a range of investment costs from £300 per ha for restoring dry heath to £5000/ha for areas where bare peat dominates. Although no literature is available on the capital costs of restoring burned peatland shortly after the fire, a positive NPV at ~ £4,000/ha capital investment costs with £220/ha annual cost is close to the high end of the range, suggests that peatland restoration will have a net benefit to society.

6 Conclusions

- The estimated wildfire area excluding open water, based on remotely sensed data, was 54.9 km^2. This wildfire area was dominated blanket bog (53.8 km^2).

- In this study there has been no assessment of burn severity, and no site visit. We have anecdotal reports that the fire was fast and light across much of the burned area, and that recovery of flora was occurring within a few weeks of the fire. We present potential carbon loss values across a range of possible scenarios reflecting different fire severities.

- From a range of published studies of carbon loss during a wildfire on peat bog, the mean of reported mid-range carbon loss values for an area equivalent to the area of the north Sutherland wildfire, was 290 kt, with reported mid-range values ranging from 124 kt to 928 kt. Using IPCC methods, the comparable mid-range carbon loss value was 230 kt with a smaller range of 174 kt to 294 kt. This was for a scenario that assumed 20% of the burned area had been drained.

- Reported values of carbon loss include values, scaled up to an area equivalent to the area of the north Sutherland wildfire, varying from 20 kt to 933 kt. The north Sutherland wildfire is understood to have been of low severity across much of the burned area, suggesting that carbon loss may have been at the low end of this range, but that there is potential for much greater losses in the event of a more severe wildfire on blanket bog.

- The IPCC default values for organic soil fuel consumption show a large difference in values between drained and undrained peat, contributing to peer-reviewed evidence for loss of carbon from wildfires on drained peat bogs being five to nine times greater than loss of carbon from wildfires on undrained peat bogs.

- To give some context to the estimated carbon loss values using IPCC methods, the low carbon loss value for the 20% drained scenario, of 174 kt is equivalent to 1.7% of the total greenhouse gas emissions for Scotland in 2017, equivalent to approximately 6.2 days of 2017 daily average greenhouse gas emissions in Scotland.

- There was close agreement in carbon loss values estimated from published reports of previous wildfires on peat bog, and carbon loss values from the Tier 1 IPCC method for emissions from fires on drained inland organic soils given in IPCC (2014). Values using data from reports of other fires had a mid-point of 290 kt C, compared with values of 204-256 kt C (mid-range values, but varying depending on the scenario for percentage of the area that was drained) using the IPCC method.

- Generally, for peatland fires that are carbon sinks, where peatland is burned severely leaving bare peat, restoration can return the ecosystem to a carbon sink more quickly than for natural regeneration through avoided loss of carbo, and carbon sequestration.

- Restoration of severely burned peatland is cost neutral up to a cost of £3,460 ha capital investment when assuming a £220 per ha annual cost.

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