

1 **Response to reviews of “Vegetation structure and fire weather influence**
2 **variation in burn severity and fuel consumption during peatland wildfires”**
3 Below our responses to the comments are shown in blue.

4 **Response to Reviewer 2**

5 The authors are very grateful to the reviewer for their constructive comments on our paper. We are
6 pleased they think it makes a valuable contribution to our understanding of the environmental
7 effects of peatland fires and that the pCBI is likely to prove useful for other researchers. Most of the
8 reviewers comments requested specific and relatively minor corrections. Page 15740, line 3: Can you
9 give any specific examples of ‘other significant environmental and human impacts’?

10 For the sake of brevity we directed readers to the excellent review by Watts & Kobziar (2013).
11 Negative human effects include respiratory problems associated with the inhalation of noxious
12 smoke (see recent reports from Indonesia) and the significant effort and costs involved in fighting
13 such fires. Environmental impacts include destruction of soil seedbanks, widespread plant mortality,
14 post-fire erosion and water pollution problems and the emission of large quantities of carbon. We
15 have added this information.

16 Page 15740, lines 9-13: Probably also worth noting that British peatlands have also been impacted by
17 other drivers of changes such as pollution, N deposition, etc.

18 Agreed, we mention this in the revised MS

19 Page 15740, line 20: You refer to ‘managed burning’ here, but elsewhere the term ‘prescribed
20 burning’ is also used. If defined differently, give definitions; otherwise, stick to one term.

21 We used the term “prescribed” to refer to the experimental fires we analysed data from. In general
22 we refer to the practice of using fire for habitat maintenance by land-managers as “managed
23 burning” as it, generally, does not have the highly technical characteristics associated with prescribed
24 burning as practiced in other countries. We have ensured we are consistent in this use of
25 terminology throughout.

26 Page 15741, lines 5 – 14: Given the confusion in the wider media with the term ‘peatland fires’ i.e.
27 whether it refers to fires that consume peat, or surface fires that consume peatland vegetation, it
28 might be worth expanding a little here to carefully explain the differences.

29 Agreed we have done so in our revised MS

30 Page 15745, lines 16-17: It might be useful to report equation 4 from Davies et al. (2008)

31 The equation is Moss and buried stem biomass = 407 + 171 x Mean M/L depth (cm). We have
32 provided this in the revised MS

33 Page 15746, line 26: It is implied that Appendix II details the various transformations used for the fuel
34 consumption data, but instead Appendix presents two figures of fuel load. Please clarify.

1 Appendix II provides dot plots which shows the distribution of individual estimates of surface and
2 ground fuel load. The skewed distributions in the plots were used as justification for the
3 transformations. We will clarify this in the revised MS

4 Page 15747, line 24: DMC and DC are not defined in the main body of the text. -

5 We have inserted the following explanation in the Introduction: "We aimed to investigate the
6 relationship between fire severity and all the sub codes and indices of the FWI System but were
7 particularly interested in its response to variation in the DMC (Duff Moisture Code) and DC (Drought
8 Code). These codes are designed to relate, respectively, to the moisture content of duff (partly
9 decomposed litter) and compacted deeper organic layers. Such fuel layers bear some resemblance to
10 the moss/litter layers and peat deposits found in British peatland ecosystems. The BUI integrates
11 DMC and DC to provide an overall indication of fuel availability."

12 Page 15748, lines 19 – 20: Does this sentence only concern itself with ground fuel combustion
13 completeness? If so update beginning of the sentence to "Ground fuel combustion completeness
14 appeared

15 The sentence in question reads "Ground fuel consumption and combustion completeness..." We are
16 referring to ground fuels in both cases. We will clarify this

17 Page 15748, line 24: BUI not defined in the main body of the text.

18 BUI is the Buildup Index from the Canadian Fire Weather Index System it relates to the availability of
19 ground fuels for consumption. See modification described above.

20 Page 15751, lines 4 – 5: Might be worth making the distinction that it is components of the FWI that
21 are useful not necessarily the full FWI.

22 Agreed, we are particularly referring to the DC and DMC

23 Table 1: Could you add the duration of the fire or the date range?

24 Unfortunately we only have the date the fire was reported available.

25 Figure 4: Caption refers to colours and shapes of points 'follows Fig 4' I assume you mean Figure 2?

26 The legend should state that colours and shapes follow Figure 3. We have corrected this.

27 **Response to Reviewer 3**

28 RESPONSE TO GENERAL COMMENTS

29 The authors are grateful to the referee for their positive and constructive review of our paper. We're
30 glad they feel it makes a useful contribution and are particularly pleased they approved of our
31 statistical analysis - that was something we put a lot of effort into getting right. The reviewer makes a
32 general comment that they'd like to see us "do more" with the GLMM but we're not really sure what
33 they mean here. The objective of the analysis was to partition variance across the spatial scales of
34 our experiment rather than to model consumption - we do that (see equations 1 and 2) using a more

1 complete data set that includes information from a wider variety of burning conditions. We feel we
2 do draw attention to the importance of within fire variation and discuss that at some length already.

3 RESPONSE TO SPECIFIC COMMENTS

4 In our response below we provide both the page and line numbering in the published BGD
5 manuscript and that quoted by the reviewer (latter in brackets)

6 Page 15739, line 25 (Page 1, Line 25) "ancient carbon"

7 We have changed this to "stored carbon" in our revised version

8 Page 15745, line 26 (Page 7, line 26) Correlation analysis

9 We used Pearson's product-moment correlation. Most of the variables are approximately normally
10 distributed except for the DMC but this is hard to judge properly given the small sample size and the
11 fact that each fire has the same DC and DMC. We could use Spearman or Kendall rank-based
12 correlations but the trade-off here is that exact P-values can't be calculated due to the tied ranks. In
13 either case the overall conclusion is the same - there are statistically significant positive correlations
14 between DMC/DC and pCBI. We have clarified we used Pearson's correlation.

15 Page 15746, line 5-6 (Page 8, line 5-6) GLMM analysis

16 The referee's comment that our analysis was conservative may stem from a misunderstanding of its
17 objectives. Our aim was to partition variance in fuel consumption across the spatial scales of our
18 experiment and to estimate the uncertainty associated with fuel consumption estimates. We have
19 clarified this in our revised manuscript by redrafting the section to clearly state the analysis' objective
20 at the outset. The reviewer makes reference to us discussing "the impacts of Calluna and Sphagnum"
21 and states that these aren't linked back to the GLMM. The relevant section of the discussion (page
22 15750, lines 6-28) was focused on the results of the GLMM and in particular on understanding the
23 relevant importance of the different random factors in our model. We have clarified on line 6 that
24 the results relate to the GLMM. We do not explicitly test for an effect of vegetation type but do
25 suggest this as a hypothesis to explain the variation in consumption we observe.

26 Page 15739, line 26 (Page 1, line 26)

27 Sentence already reads "equivalent to 25 % of global soil organic carbon stocks (Mitra et al. 2005)
28 and 75 % of all atmospheric carbon". We think writing "equivalent to" a second time would be
29 clumsy and that the meaning is already clear.

30 Page 15740, line 8(Page 2, line 8) "...far from being undisturbed..."

31 We have changed this to read "Temperate peatlands are also an important carbon store and habitat
32 type but have a long history of disturbance and management"

33 Page 15742, line 19 (Page 4 line 19)

1 Table 1 describes which sites are in England and which in Scotland. We modified the para- graph to
2 explain that all sites were in Britain and have removed reference to the UK (not the same thing) to
3 avoid confusion

4 (Page 5 line 3)

5 We're not sure if there's a convention around the formatting of cited R package names either but
6 have always used quote marks in the past

1

2 **Vegetation structure and fire weather influence variation in**
3 **burn severity and fuel consumption during peatland**
4 **wildfires**

5

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19

20 **Abstract**

21 Temperate peatland wildfires are of significant environmental concern but information on
22 their environmental effects is lacking. We assessed variation in burn severity and fuel
23 consumption within and between wildfires that burnt British moorlands in 2011 and 2012. We
24 adapted the Composite Burn Index (pCBI) to provide semi-quantitative estimates of burn
25 severity. Pre- and post-fire surface (shrubs and graminoids) and ground (litter, moss, duff)

1 fuel loads associated with large wildfires were assessed using destructive sampling and
2 analysed using a Generalised Linear Mixed Model (GLMM). Consumption during wildfires
3 was compared with published estimates of consumption during prescribed burns. Burn
4 severity and fuel consumption were related to fire weather, assessed using the Canadian Fire
5 Weather Index System (FWI System), and pre-fire fuel structure. pCBI varied 1.6 fold
6 between, and up to 1.7 fold within, wildfires. pCBI was higher where moisture codes of the
7 FWI System indicated drier fuels. Spatial variation in pre- and post-fire fuel load accounted
8 for a substantial proportion of the variance in fuel loads. Average surface fuel consumption
9 was a linear function of pre-fire fuel load. Average ground fuel combustion completeness
10 could be predicted by the Buildup Index. Carbon release ranged between 0.36 kg C m^{-2} and
11 1.00 kg C m^{-2} . The flammability of ground fuel layers may explain the higher C release-rates
12 seen for wildfires in comparison to prescribed burns. Drier moorland community types appear
13 to be at greater risk of severe burns than blanket-bog communities.

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14 1 Introduction

15 Peatland wildfires pose a significant global challenge due to their potential for severe effects
16 on ecosystem functioning and the detrimental role they may play in climate change. Peatlands
17 account for approximately 2.5 % of Earth's land-cover (Kaat and Joosten 2009) and contain
18 more than 600 Gt of ancient stored carbon (Yu et al. 2010), equivalent to 25 % of global soil
19 organic carbon stocks (Mitra et al. 2005) and 75 % of all atmospheric carbon (Kaat and
20 Joosten 2009). The degradation of this resource is a potential positive feedback to climate
21 change and smouldering wildfires also have other significant environmental and human
22 impacts such as respiratory problems associated with the inhalation of noxious smoke, the
23 significant effort and costs involved in fire fighting, destruction of soil seedbanks, widespread
24 plant mortality and post-fire erosion and water pollution problems (Watts and Kobziar 2013).
25 Increased fire risk and severity with climate change means wildfires pose a particularly
26 significant threat to the ecological integrity and carbon stocks of peatlands (Turetsky et al.
27 2015).

28 The majority of research on the effects of peatland wildfires has come from tundra, boreal and
29 tropical ecosystems (Turetsky et al. 2015). Temperate peatlands are also an important carbon
30 store and habitat type but many are far from being undisturbedhave a long history of
31 disturbance and management (e.g. Moore 2002). British, peatlands are acknowledged to be of
32 significant national and international conservation importance though most have been

1 subjected to a variety of land management practices, including burning and grazing, over at
2 least the last two² centuries (Bonn et al. 2009). Many peatlands have also been significantly
3 impacted by drainage (Holden et al. 2004) and nutrient deposition from atmospheric pollution
4 (Hogg et al. 1995). These British peatland habitats contain fire-prone vegetation including
5 moorlands dominated by *Calluna vulgaris* L. Hull (hereafter *Calluna*) and a variety of mire
6 and bog communities associated with *Molinia caerulea* (L.) Moench and *Eriophorum* spp.
7 The majority of such habitats are underlain either by deep peat deposits or by shallower
8 organic soils that nevertheless hold substantial amounts of carbon. Estimates suggest that
9 around 88 t C ha⁻¹ are stored in the soil and up to 2 t C ha⁻¹ in the vegetation of dwarf shrub
10 dominated moorlands in the UK (Ostle et al. 2009). The majority of the U.K.'s 4.5 Tg of soil
11 carbon stocks are stored in peat deposits below heath, bog and moorland habitats (Bradley et
12 al. 2005). Managed burning is an important control on the structure of these habitats with fires
13 burnt regularly in both moorland and blanket bog habitats systems (Bonn et al. 2009).
14 Recommended burn rotations are 15-25 years for *Calluna*-dominated moorlands whilst longer
15 rotations or no burning are recommended for wetter bog communities (Scottish Government
16 2011). The role of fire in peatland ecology has become a highly controversial subject with
17 substantial debate surrounding the effect of managed burning on ecosystem dynamics (e.g.
18 Grant et al. 2012). The situation is not helped by a lack of data on how fire affects temperate
19 peatland ecosystems such as those found in the UK. A number of studies have been
20 completed but mostly for low severity managed experimental prescribed burns (e.g. Davies et
21 al. 2010) or, for a few individual wildfire events (e.g. Davies et al. 2013, Maltby et al. 1990,
22 Worrall et al. 2011). There is a consensus that wildfires pose a substantial and growing threat
23 in the context of a changing climate (Bonn et al. 2009). In this context, data is urgently-
24 needed on both the scale of the wildfire problem and the effects of such burns.

25 In systems with peat or organic soils severe wildfires that ignite carbon-rich deposits can lead
26 to substantial, instantaneous losses of carbon (Davies et al. 2013) and long-term changes to
27 ecosystem function (Maltby et al. 1990). Whilst the severe effects of smouldering peat fires
28 are obvious, such burns lie at one end of a spectrum of burn severity and not all fires on
29 peatlands necessarily ignite peat or cause ecological damage. Indeed carefully managed
30 burning of peatlands can have a variety of ecosystem benefits (Davies et al. 2008a).
31 Differences in burn severity can be caused by between and within site variation in fuel type
32 and fuel structure as well as by differences in fire weather conditions (e.g. fuel moisture
33 content, wind speed) across different burn days (Davies et al. 2010). In general this may mean

1 that managed fires, typically burnt during low-severity conditions, have more limited effects
2 than wildfires patterns are not consistent as wildfires can occur in a wide variety of conditions
3 and not all have particularly severe effects. Rather little effort has been made to try to capture
4 or understand the effects of such variation but this is vital in order to monitor the amount of
5 carbon released during wildfires and the extent of the environmental change they cause.

6 This research was initiated following severe wildfires during the springs of 2011 and 2012.
7 We aimed to assess how burn severity varied within and between individual wildfires, and to
8 define what the implications of such variation might be for carbon emissions due to wildfire
9 and on-going development of fire danger rating systems such as the Met Office Fire Severity
10 Index (MOFSI; Kitchen et al. 2006). MOFSI is based on the Canadian Fire Weather Index
11 System (FWI System; Van Wagner 1987) and has been implemented in Wales and England in
12 order to provide a forecast of “exceptional” conditions when it becomes permissible to close
13 open-access land under the Countryside and Rights of Way Act 2000. To date there have been
14 limited efforts to examine the relationship between the FWI System and fire severity in the
15 UK. There is some evidence its moisture codes relate fairly well to ground fuels’ (Legg et al.
16 2007) and peat (Krivtsov et al. 2008) moisture content, and that it can do a tolerable job of
17 discriminating periods of increased wildfire risk (Legg et al. 2007). We aimed to investigate
18 the relationship between fire severity and all the sub codes and indices of the FWI System but
19 were particularly interested in its response to variation in the DMC (Duff Moisture Code), the
20 DC (Drought Code) and the BUI (Build-up Index). The DMC and DC are designed to relate,
21 respectively, to the moisture content of duff (partly decomposed litter) and compacted deeper
22 organic layers. Such fuel layers bear some resemblance to the moss/litter layers and peat
23 deposits found in British peatland ecosystems. The BUI integrates DMC and DC to provide
24 an overall indication of fuel availability. Our specific objectives were to: develop a simple
25 methodology to assess variation in burn severity post-hoc; assess the extent to which burn
26 severity and fuel consumption vary within and between wildfires; and to investigate links
27 between burning conditions (fuel type and fire weather) and variation in burn severity and
28 fuel consumption.

1 2 **Material and methods**

2 **2.1 Study sites**

3 Monitoring was completed on five different wildfires (Table 1) that burnt [British peatlands](#)
4 during the springs of 2011 and 2012. Sites were selected from information on fires provided
5 by land-managers, public and private land-owners, government agencies and Fire and Rescue
6 Services. We selected five sites that represented fires displaying moderate to high burn
7 severity and the North-South and West-East range of bioclimatic conditions of the British
8 uplands.

9 Pre-fire biotic and abiotic conditions varied both within and between our study sites (Table 1).
10 Most locations in England were broadly classified as mires on deep peat with vegetation
11 dominated by *Calluna* and *Eriophorum vaginatum* L. along with species such as *Vaccinium*
12 *myrtillus* L., *Deschampsia flexuosa* (L.) Trin. and *Trichophorum caespitosum* (L.) Hartm.
13 Vegetation was underlain by mats of pleurocarpous mosses. A number of plot locations were
14 recorded at noticeably wetter locations. Here *Calluna* was less dominant, *Eriophorum* spp.
15 and *T. caespitosum* occasionally very abundant and ground layer vegetation included patches
16 of *Sphagnum*. Sites in Scotland represented opposite ends of the spectrum of peatland habitat
17 types found in [the UK](#)[Britain](#). Finzean was comparatively drier, had shallow, stony organic
18 soils and vegetation dominated by a mixture of *Calluna* and *Pteridium aquilinum* (L.) Kuhn.
19 The site at Loch Doon was a bog with true peat soils and vegetation dominated by *Molinia*
20 *caerulea* (L.) Moench, *Myrica gale* L. and *Sphagnum* spp.

21 **2.2 Field data collection**

22 Burn severity and fuel consumption sampling was performed approximately 6 months after
23 the fires occurred. Previous researchers have collected such data as much as a year after fire
24 (e.g. de Groot et al. 2009). Wildfires are sporadic, unpredictable events meaning sites had not
25 been surveyed prior to the burns. Similarly to other studies (e.g. Kasischke and Johnstone
26 2005, Hollis et al. 2007, de Groot et al 2009), we used paired plots with burnt/unburnt
27 subplots located across the fire perimeter (see Supplementary Material Figure 1). Two or
28 three paired plots were located within each fire and chosen to represent the range of burn
29 severities visible during a detailed site reconnaissance with local stakeholders. Many
30 peatlands in the British uplands have a patchwork of fuel structures produced by managed

1 burning. We were therefore careful to ensure that subplots were established where, following
2 observation of stem basal diameters, stem density and discussion with local land-managers,
3 we were confident that pre-fire fuel conditions across the fire-line were similar. Plots were
4 also only established in regions of the fireline known to have been actively extinguished. In
5 order to capture additional information about variation in burn severity we established a
6 number of unpaired plots within the interior of each fire (Table 1). Unburnt areas were not
7 available for comparison with these plots and they were only used to explore variation in burn
8 severity.

9 **2.3 Fire weather**

10 Variation in burning conditions between the fires was described using the FWI System (Van
11 Wagner 1987). The FWI System requires daily data on wind speed, temperature and humidity
12 at 12 noon as well as 24-hour accumulated rainfall. These were extracted from the British
13 Atmospheric Data Centre database for the nearest weather station to each of the wildfires
14 (mean distance = 15 km, max = 31 km). Rainfall data were available from rain gauges closer
15 to the fire site than the nearest full weather station and these to estimate precipitation (mean
16 distance = 5 km, max = 10 km). Available data on 24 hour accumulated rainfall was 09:00-
17 09:00 rather than noon to noon though the difference is unlikely to be of importance. FWI
18 System values were calculated using the package “fume” (Santander Meteorology Group
19 2012) in R 3.1.2 (R Development Core Team 2014). Some of the moisture codes and indices
20 of the FWI System have long lag times (52 days for the Drought Code) so values were
21 calculated with a 90 day lead-in.

22 **2.4 Assessing burn severity**

23 To assess burn severity we adapted the Composite Burn Index (Key and Benson 2006) which
24 was developed in the USA to allow semi-quantitative assessment of burn severity and ground-
25 truthing of remotely sensed data (e.g. Miller and Thode 2007). The CBI uses a scoring system
26 to visually estimate a fire’s impact on components of each five fuel strata. For instance,
27 assessment of “substrates” considers consumption of downed fuels of a variety of size classes
28 (litter up to heavy fuels > 8 inches diameter), consumption of duff layers and changes to the
29 cover and colour of soil and rock. Similarly to Schepers et al. (2014), we adapted the CBI to
30 account for the unique vertical structure and fuelbeds of treeless peatland habitats and,
31 specifically, to include the impact of fire on peat-building *Sphagnum* species. We recorded

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1 severity in circular plots 20 m in diameter (Supplementary Material, Figure S1) according to
2 two strata – substrates (soil, litter and mosses) and the field layer (dwarf shrubs and
3 graminoids; see Supplementary Material, Table S1). All variables were rated on a scale of 1-3
4 with individual ratings averaged within strata and then summed across the strata. Any variable
5 that was not relevant, or which could not be recorded, for a particular plot was disregarded. A
6 full protocol and data collection sheet for using the peatland CBI methodology (pCBI) are
7 provided in the Supplementary Material.

8 **2.5 Estimating fuel consumption**

9 We assessed fuel consumption in two pCBI burnt-unburnt paired plots for each fire. Within
10 both the burnt and unburnt subplots we randomly located two fuel quadrats (0.25 m²) and five
11 gas-flux chambers (0.12 m²). All biomass above the top of the peat was harvested in each
12 quadrat/chamber. A total of fourteen biomass estimates were thus available for each plot -
13 seven from burnt and seven from unburnt subplots. Harvested vegetation was separated into
14 the following categories: dwarf shrubs, graminoids, ferns (*P. aquilinum*), pleurocarpous
15 mosses and plant litter, *Sphagnum* spp., tussock bases of *M. caerulea* and/or *Eriophorum* spp.
16 and woody stems buried in the moss and litter. During analysis, the first three categories were
17 grouped into a surface fuel category whilst the mosses, litter, tussock bases and buried stems
18 were classified as ground fuels. Material was dried for 48 h at 80 °C.

19 Fuel consumption in our wildfires was compared with values reported by Legg et al. (2007)
20 for 26 experimental prescribed burns in *Calluna*-dominated moorland fuel types. Legg et al.
21 (2007) used a non-destructive method, based on visual obstruction of a measuring stick
22 (Davies et al. 2008b), to estimate pre-fire surface and ground fuel loads. Post-fire surface fuel
23 loads were estimated via destructive harvesting. We estimated ground fuel consumption in
24 these fires by using the reported mean change in moss/litter layer depth following burning and
25 ~~the equation four in in the equation in~~ Davies et al. (2008) which relates moss/litter layer depth
26 (D_m , cm) to ground fuel biomass (B_g , g m⁻²; equation 1).

$$27 B_g = 407 + 171 \times D_m \quad (1)$$

28 **2.6 Data analysis**

29 We analysed burn severity data at the plot-level, in essence treating each plot as a separate
30 observation of fire effects and burn severity. We believe that this is valid because substantial

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1 variations in vegetation type and fuel structure across the fire ground and changes in fire
2 weather during the course of the burn day mean fire behaviour can be considered independent
3 at each plot. This approach is frequently used in wildland fire research as obtaining numerous
4 observations of individual fires is often impossible (e.g. Fernandes et al. 2000, de Groot et al.
5 2009). The relationship between pCBI and FWI system codes was analysed graphically and
6 using correlation analysis ([Pearson product-moment correlation in the “cor.test” function in R](#)
7 3.1.2; R Core Team 2014).

8 We used a Generalised Linear Mixed Model (GLMM) with a normal error distribution to
9 investigate spatial variation in estimated fuel consumption. [The aim of our analysis was to](#)
10 [partition variance in our data to understand how fuel consumption varies](#) [We were specifically](#)
11 [interested in how variation in fuel structure](#) at multiple scales (i.e. between fires, plots within
12 fires and within plots) [and how this contributes to uncertainty in estimates of fuel](#)
13 [consumption. We were not interested in testing the hypothesis that there is a difference in](#)
14 [biomass between burnt and unburnt plots as this is not particularly enlightening](#) [contributed to](#)
15 [uncertainty in estimates of fuel consumption](#). The GLMM was run with plot and fire site were
16 defined as random effects whilst status (burnt/unburnt) and sample type (chamber/quadrat)
17 were defined as fixed effects. Including plot as a random effect accounts for the paired burnt-
18 unburnt subplots design of our experiment. We selected the best fitting model by comparing a
19 full model and a minimal model. The minimal model contained all sources of variation
20 intrinsic to the design: the main effects of status and sample type, and random intercepts at the
21 plot and fire levels. The full model additionally allowed the effect of status to vary between
22 sample types (fitted as an interaction between status and sample type), and between plots and
23 fires (fitted as random slopes at the plot and fire levels). Analysis started with the full model
24 and simplification proceeded by null hypothesis testing, dropping non-significant effects.
25 Random effects were tested first, using parametric bootstrapping with 10,000 replicates
26 (Faraway 2005), dropping effects where $P > 0.1$. Fixed effects were then tested using
27 likelihood ratio tests, dropping effects where $P > 0.05$. We justify using a less stringent
28 significance level for random effects on the basis that power for testing random effects is
29 generally low with few random effect levels, and incorrectly dropping a random effect due to
30 a false negative test result can result in over-precise (anti-conservative) fixed effect estimates
31 (Schielzeth and Forstmeier 2009). We used parametric bootstrapping with 10,000 replicates to
32 estimate confidence intervals around mean plot-level consumption. This process was used to
33 fit separate models for both ground and surface fuel consumption. Fuel consumption was

1 square-root transformed to improve the fit of the residuals to a normal distribution. Log
2 transformation was also considered but provided a poorer fit (see Appendix II [for dot plots](#)
3 [showing the raw data distributions](#), Supplementary Material). There is debate in ecology
4 about the usefulness of P-values (Ellison et al. 2014) and we do not report them ~~as testing the~~
5 ~~hypothesis that there is a difference in the biomass of burnt and unburnt plots is not~~
6 ~~particularly enlightening~~. Rather we report the explanatory power of the final selected models
7 and the variance explained by different levels of our experimental design. Thus, for the final,
8 reduced models we used the procedures described by Nakagawa & Schielzeth (2013) and
9 Johnson (2014) to calculate marginal and conditional R² values. These describe the
10 explanatory power of the fixed effects and the whole model (fixed + random effects)
11 respectively. As an initial step in this analysis we were also able to partition the variance in
12 our data into that related to the fixed effects and the random effects of plot and fire. We
13 assumed that residual variance was the result of within subplot variation in load between
14 samples.

15 We examined controls on mean fuel consumption by combining the estimates of fuel
16 consumption during wildfires produced by the GLMM analysis with information available
17 from the prescribed fires reported by Legg et al. (2007). This allowed us to examine how
18 mean ground and surface fuel consumption varies over a wider range of fire weather
19 conditions. We used the “lm” function in R to model changes in the consumption and
20 combustion completeness of surface and ground fuels as a function of pre-fire fuel load and
21 fire weather.

22 3 Results

23 3.1 Variation in burn severity

24 There was substantial variation in burn severity both within and between individual fires
25 (Figure 1). On average, mean pCBI varied 1.6 fold between wildfires but up to 1.7 fold within
26 fires. Variability in burn severity was particularly substantial in the Anglezarke and Loch
27 Doon wildfires. Examining the relationship between plot vegetation community, fire weather
28 conditions and pCBI suggested potential interactions between these variables (Figure 2). In
29 general, pCBI appeared to increase with higher DMC ($r = 0.80$, $P = 6.4 \times 10^{-4}$) and DC ($r =$
30 0.68 , $P = 7.9 \times 10^{-3}$) values. Plots in drier *Calluna*-dominated communities (National
31 Vegetation Community H12) appeared to burn at high severities at lower DMC and DC

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1 values than wetter bog and mire communities (NVC M19, M20, M25a). However, fire sites
2 with more varied vegetation community structure did not necessarily show the greatest
3 amount of variation in fire severity.

4 **3.2 Variation in fuel consumption**

5 Both surface and ground fuel consumption were best represented by a model which included
6 the fixed effects of plot status (burnt/unburnt), sample type (quadrat/chamber), random
7 intercepts for individual fires and plots within fires, and random slopes for the effect of status
8 within individual plots (Table 2). Plot status had considerably greater explanatory power for
9 surface fuel loads compared to ground fuel loads where random factors attributable to
10 variation in load between fires, plots and samples explained a greater proportion of the
11 variance. There was considerable variation in fuel consumption both within and between
12 different wildfires (Figure 3), indeed variability within some fires was greater than that seen,
13 on average, between fires.

14 For surface fuels there was a positive linear relationship between pre-fire fuel load and mean
15 fuel consumption irrespective of fire type (Figure 4). Surface fuel consumption (C_s) was best
16 predicted by pre-fire fuel load (L_s ; $R^2_{adj} = 0.73$, $P = 1.79 \times 10^{-11}$; Equation 24). None of the
17 FWI System values were significant or substantially improved the model fit. For ground fuels,
18 the relationship between pre-fire fuel load and mean fuel consumption was noticeably
19 different with a positive, linear relationship for wildfires but little change in consumption with
20 load for prescribed fires (Figure 4). Ground fuel consumption and ground fuel combustion
21 completeness appeared to decline with ground fuel load (Figure 4). It proved difficult to
22 develop a satisfactory model of ground fuel consumption, but ground fuel combustion
23 completeness (P_g) could be predicted tolerably well as an asymptotic function of BUI (B; R^2_{adj}
24 = 0.77, $P = 1.77 \times 10^{-12}$; Equation 32).

25
$$C_s = 0.173 + 0.624 \times L_s. \quad (24)$$

26
$$P_g = \sqrt{-0.034 + 0.020 \times B}, \quad (32)$$

27 **4 Discussion**

28 Wildfires are variable in every aspect and the fires we were able to assess do not capture the
29 full range of possible conditions. Notably, none of our fires displayed peat smouldering
30 outside of isolated “hotspots”. Nevertheless, this work represents the first multi-site attempt to

1 investigate the relationship between burning conditions and wildfires' ecosystem effects on
2 moorlands. Wildfires on peatlands are recognised as a growing global challenge with the
3 potential to develop into a significant positive feedback to climate change (Kettridge et al.
4 2015). Scientists and land-managers currently have limited understanding of the extent and
5 causes of variation in the severity and ecological effects of temperate peatland fires.
6 Temperate peatlands, such as those found in the UK, are likely to be at the forefront of the
7 effects of climate change with some studies suggesting considerable declines in their
8 bioclimatic space (Gallego-Sala and Prentice 2013) and fundamental changes in state
9 associated with even moderate reductions in water tables (Kettridge et al. 2015). UK
10 peatlands are of particular management concern due to the substantial area that has already
11 been lost or degraded by changing land-management, and debates over the effects of
12 traditional managed burning on the ecosystem services they provide (Bonn et al. 2009).

13 The growing peatland wildfire problem demands evidence to inform management and solve
14 on-going conflict about the impacts of burning. Our adapted version of the CBI provides a
15 method for rapid cataloguing of post-fire effects and burn severity in UK peatland
16 ecosystems. The pCBI method appeared to function well and detected substantial differences
17 in burn severity between and within individual fires. Importantly, there was evidence that
18 increased pCBI can be attributed to reduced ground fuel layer moisture content as higher burn
19 severity was recorded at higher values of DMC and DC (Figure 2). Our results, and existing
20 evidence that the DC may relate to the potential for smouldering peat fires (Davies et al.
21 2013), raise the prospect that it will be possible to forecast the potential for damaging
22 wildfires. There was also a suggestion that burn severity is a function of ecosystem type, and
23 associated site hydrology, as we recorded higher severity burns in dry moorland sites than
24 would be expected given the intermediate DMC/DC values at which they occurred (Figure 2).
25 Sites with thin organic soils may thus be at greater risk of severe and smouldering wildfires
26 than those with deeper peat and forecasts for such systems should be developed separately.

27 **4.1 Variation in fuel consumption**

28 In general, the random factors in our GLMM, that accounting for variation in loads within
29 plots; and within and between fires, accounted explained for as much, if not more, of the
30 variation in fuel loads across our survey than differences in fuel load between burnt/unburnt
31 subplots. This was particularly true for ground fuels where 70% of the variance was
32 attributable to spatial variation rather than the effects of fire or sample type. For ground fuels,

1 the higher variance explained by random factors is possibly a function of the substantial
2 differences in their composition between sites and, at some locations, between plots. Our sites
3 included both bog communities with substantial cover of *Sphagnum* spp. and drier sites with
4 thin organic soils where bryophyte communities were poorly-developed and ground fuels
5 were dominated by litter. When considering the wildfires alone, ground fuel consumption
6 showed a linear relationship with pre-fire fuel load though there was some evidence of a
7 possible interaction with ecosystem type. Shetler et al. (2008) demonstrated that the presence
8 of *Sphagnum* had a limiting effect on total carbon release during fires in black spruce forest
9 peatlands and combustion completeness was lowest at Loch Doon, the wettest of our sites,
10 where *Sphagnum* spp. and *Molinia* tussocks comprised a substantial proportion of the ground
11 fuel load (Figure 4). However, this fire also occurred under the least severe fire weather
12 conditions (Figure 2).

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13 When we analysed ground fuel consumption for the wild and prescribed fires together we
14 were unable to develop a tolerably robust model. We hypothesise that this was due to
15 differences in combustion rates between ecosystem types. Given that all our prescribed fires
16 were in drier *Calluna*-dominated heathlands, our current data set was not sufficient to model
17 ecosystem-specific rates. de Groot et al. (2009) examined variation in ground fuel
18 consumption, albeit in non-peatland systems, and also found differences in the controlling
19 relationships for different fuel types. We were, however, able to predict combustion
20 completeness based on BUI. These results are significant because: i) it provides further
21 evidence that the moisture status of ground fuel layers is a critical control on burn severity in
22 peatlands; ii) it further demonstrates that certain components of the FWI System (DMC, DC
23 and BUI) may be useful in forecasting potential burn severity.

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24 Surface fuel consumption also showed significant spatial variation, though variability
25 between plots explained a greater proportion of the variance than that between fires (Table 2).
26 Surface fuel consumption of shrubs and graminoids was strongly related to pre-fire fuel load
27 (Figure 4, Equation 24) and there was no significant effect of fire weather conditions. This
28 matches some of our existing understanding of fire behaviour in moorland fuel types (Legg et
29 al. 2007). In the vast majority of cases a relatively constant proportion of fuel is consumed as
30 the fire spreads through the *Calluna* canopy consuming fine fuel particles but leaving larger
31 live basal stems unburnt. Coarser fuels form a larger proportion of the fuel in older stands
32 (Davies et al. 2008b) but rarely burn except under exceptionally severe conditions. This

1 accounts for the decline in combustion completeness with increasing fuel load (Figure 4). The
2 variability we recorded in fuel consumption within and between our fires is likely to be
3 attributable to i) differences in fuel load between ecosystems; and ii) the highly-managed
4 nature of many UK peatlands where rotational patch burning produces a mosaic of
5 fuel/habitat loads across the landscape

6 Assuming that the approximate carbon content of our fuels was 49% (Worrall et al. 2013), our
7 data suggests that average carbon release from the combustion of above-ground biomass by
8 wildfires can range between 0.36 kg C m^{-2} and 1.00 kg C m^{-2} . This is a somewhat greater than
9 seen for the prescribed fires which saw C release rates of between 0.26 kg C m^{-2} and 0.66 kg C m^{-2} . Our wildfire C release rates are considerably higher than the mean release of 0.15 kg C m^{-2} reported by Clay and Worrall (2011) for the single moorland wildfire they studied, but
10 both their result and ours falls within the range reported by Poulter et al. (2006) for a
11 temperate peatland wildfire in North Carolina, USA. Whether or not leaving a peatland
12 unburnt would increase the amount of carbon stored in the landscape is difficult to judge from
13 our data alone. Whilst unmanaged peatlands may store greater amounts of C in surface and
14 ground fuel layers than those that are subject to regular managed burning, they may also be
15 more susceptible to large-scale wildfires because of their unmanaged fuel loads (Allen et al.
16 2013). Our results show rates of fuel consumption during such wildfire events will also be
17 higher.
18

20 **5 Conclusions**

21 Burn severity varies considerably in relation to fuel structure and fire weather. To date much
22 of the research on the effects of fire on moorlands has drawn an artificial distinction between
23 the effects of prescribed burning and wildfires, though the latter do seem to be associated with
24 increased severity. Our results suggest that critical differences in burn severity and fuel
25 consumption can be linked to the flammability of ground fuel layers. Our data add to the
26 information available to researchers modelling the effects of land-management and fire
27 regimes on ecosystem carbon dynamics but we urge caution in their use and suggest that
28 further work to determine linkages between burning conditions and both short- and long-term
29 fire effects is urgently needed in temperate peatland ecosystems.

30 **6 Author contributions**

31 GMD designed the study, assisted with fieldwork, analysed the data and wrote the
32 manuscript; RD completed the fieldwork and assisted in analysing the data and writing the

1 manuscript; PJ designed the mixed effects modelling element of the analysis and wrote the
2 paper; AG designed the study and helped write the paper.

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12 [improve our manuscript](#)

13

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1 **Table 1:** Summary of wildfires used in this study including variation in biotic and abiotic conditions across the fire grounds and the monitoring effort associated with each
 2 fire. Vegetation type is reported as National Vegetation Classification (NVC) communities (Rodwell 1991) with the NVC code given in brackets. Paired CBI plots were
 3 those placed around the fire perimeter to enable direct comparison of burnt and unburnt fuel loads and soil gas fluxes. Stand-alone CBI plots were additional plots located
 4 within the fire in order to give a more comprehensive overview of variation in burn severity. Nearby unburnt comparison locations were not available for these plots

Fire name and Location	Latitude and Longitude	Date of fire	Burned area (ha)	Elevation (m)	Soil	Vegetation type	Paired CBI plots	Stand-alone CBI plots
Anglezarke (N England)	53.658°N 2.569°W	29/Apr/2011	4,144	270 - 380	Deep peat	<i>Calluna vulgaris</i> - <i>Eriophorum vaginatum</i> blanket mire (M19)	3	4
Mardsen (N England)	53.596°N 1.976°W	09/Apr/2011	316	385 - 480	Deep peat	<i>Calluna vulgaris</i> - <i>Eriophorum vaginatum</i> blanket mire (M19) <i>Calluna vulgaris</i> - <i>Vaccinium myrtillus</i> heath (H12)	3	2
Loch Doon (SW Scotland)	55.214°N 4.393°W	29/May/2011	No data	230 - 250	Shallow peat	<i>Molinia caerulea</i> - <i>Potentilla erecta</i> mire (M25a)	2	2
Wainstalls (N England)	53.777°N 1.928°W	30/Apr/2011	82	385 - 420	Deep peat	<i>Calluna vulgaris</i> - <i>Eriophorum vaginatum</i> blanket mire (M19) Scattered <i>Calluna vulgaris</i> - <i>Vaccinium myrtillus</i> heath (H12)	3	3

Finzean (NE Scotland)	57.025°N 2.702°W	30/Mar/2012	19	320 - 340	Rocky organic	<i>Calluna vulgaris</i> - <i>Vaccinium myrtillus</i> heath (H12)	3	0
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1

2

1 Table 2: Summary of the linear mixed model analyses on surface and ground fuel
 2 consumption showing, top - the proportion of variance explained by each component of the
 3 models (the marginal and conditional R^2 , respectively, show the explanatory power of the
 4 fixed effects and the whole model); and bottom – the magnitude of the fixed-effects' terms in
 5 the model where “Estimate” is the increase in the square-root of fuel load in comparison to
 6 the reference level (Burnt or Gas flux chamber for status and sample type respectively).

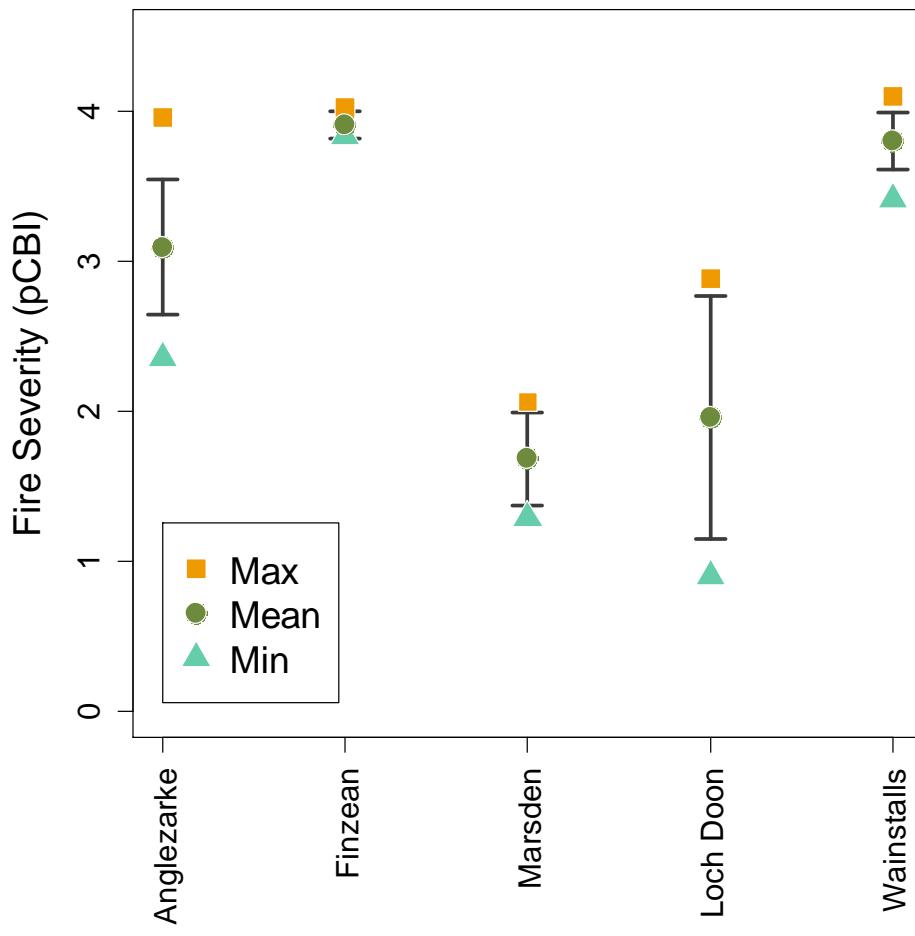
Model	Fixed effects (marginal R^2)	Random effects		Fixed + random effects (conditional R^2)	Residual
		Fire	Plot		
Surface fuels	48	5	24	77	23
Ground fuels	30	12	29	71	29

7

Model	Fixed effect	Estimate	S.E.	t
Surface fuels	Status - Unburnt	0.51	0.056	9.11
	Sample — Quadrat	0.11	0.034	3.27
Ground fuels	Status - Unburnt	0.49	0.074	6.62
	Sample - Quadrat	0.10	0.046	2.23

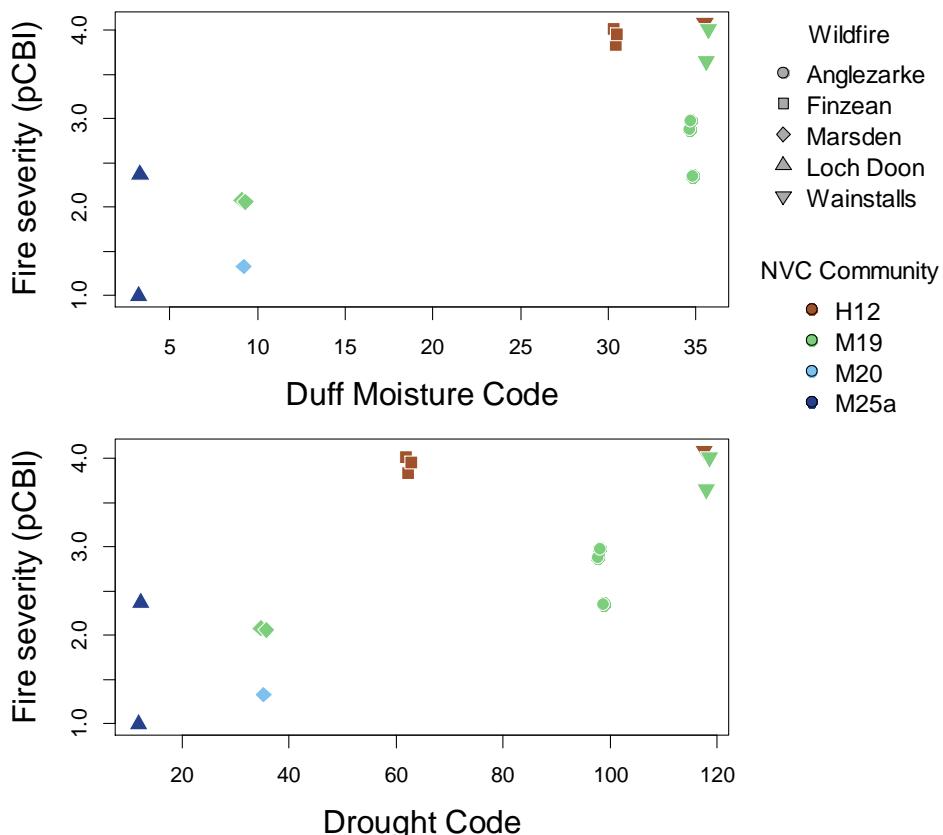
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9



1
2 Figure 1: Variation in burn severity (peatland Composite Burn Index; pCBI) within and
3 between five UK wildfires and across all 25 paired and unpaired pCBI plots, estimated using
4 the peatland Composite Burn Index. Error bars are 95% confidence intervals for the mean.
5

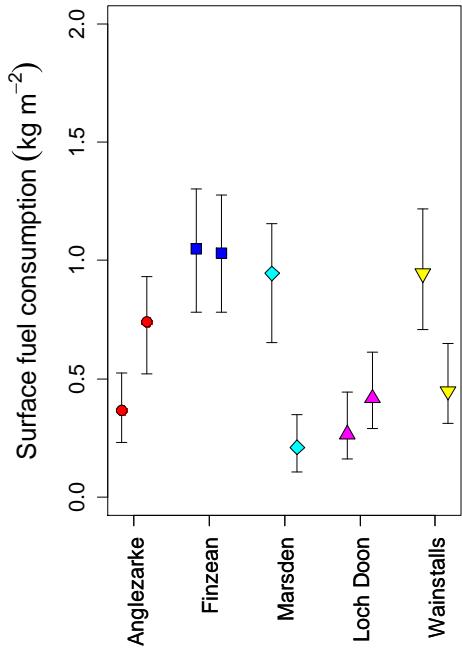
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2

3 Figure 2: The relationship between burn severity as estimated by the peatland Composite
4 Burn Index, ecosystem type (National Vegetation Classification community; Rodwell 1991)
5 and moisture codes of the Canadian Fire Weather Index system. Only data for the 14 paired
6 burnt-unburnt pCBI plots were available. Codes shown are the Duff Moisture Code (DMC;
7 relating to loosely compacted organic layers of moderate depth) and the Drought Code (DC;
8 relating to the moisture content of peat and layers of organic soil). Individual wildfires are
9 shown as different symbol shapes, colours relate to NVC vegetation community (see Table 1
10 for NVC community descriptions).

1

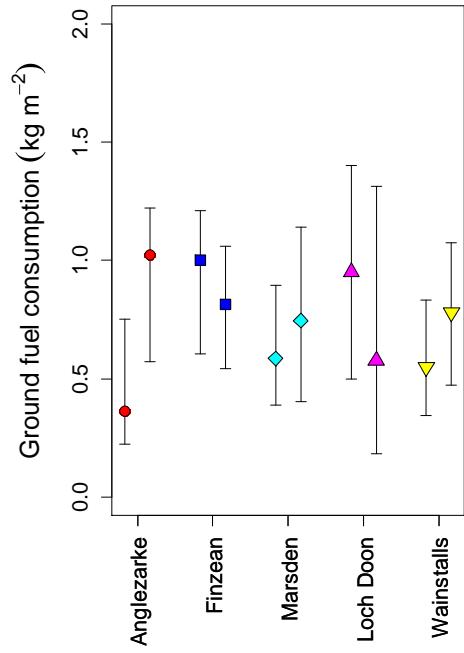


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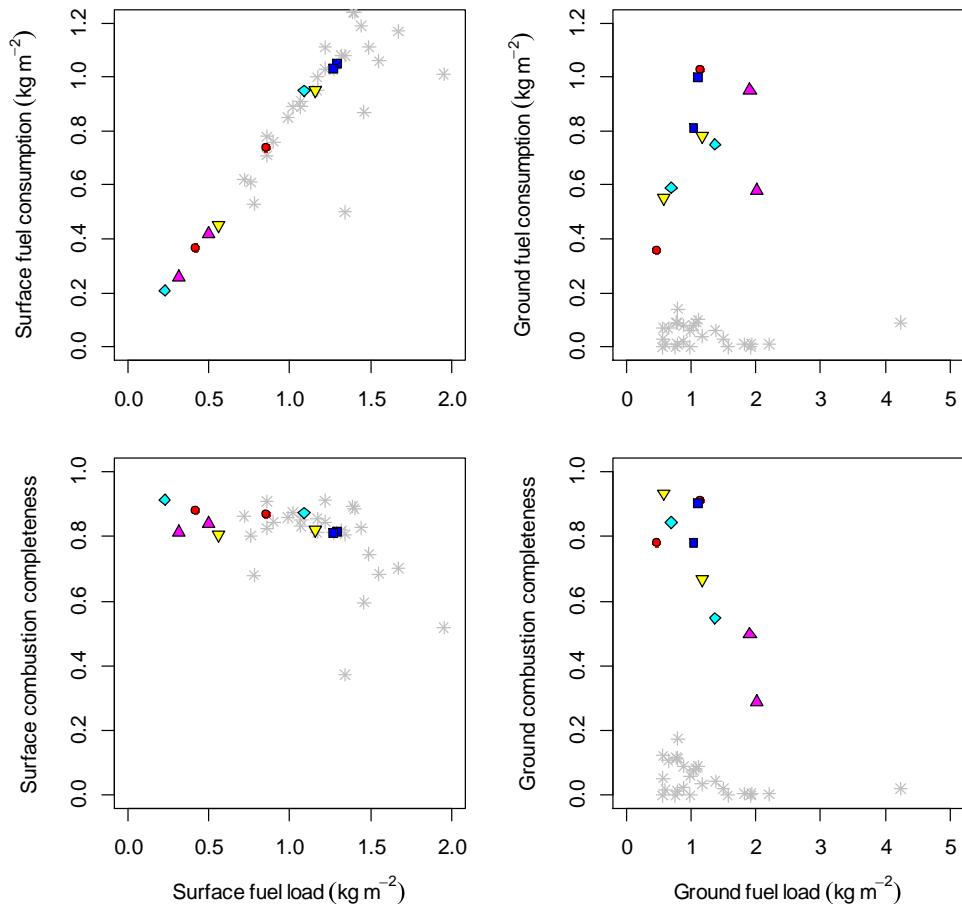
3 Figure 3: Estimated mean consumption of (left) surface, and (right) ground fuels across two
4 plots on each of five UK wildfires. Error bars are 95% confidence intervals estimated using
5 parametric bootstrapping based on a general linear mixed model analysis of variation in
6 consumption (Table 3).

7

8



1



2

3 Figure 4: The relationships between mean pre-fire fuel load and mean fuel consumption for
4 surface and ground fuels (top left and right respectively); and mean pre-fire fuel load and
5 mean combustion completeness of surface and ground fuels (bottom left and right). Stars are
6 experimental prescribed burns (see Legg et al. 2007), all other symbols are wildfires. The
7 colours and shapes of the points for wildfires follows Figure 34.

8