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Research Note

Quantitative charcoal reflectance measurements better link to regrowth potential than ground-based fire-severity assessments following a recent heathland wildfire at Carn Brea, Cornwall, UK

Stacey L. New[A,B], *Victoria A. Hudspith*[A] and *Claire M. Belcher*[A]

[A]wildFIRE Lab, Hatherly Laboratories, Department of Geography, College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4RJ, UK.
[B]Corresponding author. Email: s.new@exeter.ac.uk

Abstract. Charcoal has recently been suggested to retain information about the fire that generated it. When looked at under a microscope, charcoals formed by different aspects of fire behaviour indicate different ability to reflect the amount of light when studied using the appropriate technique. It has been suggested that this method, charcoal reflectance (Ro), might be able to provide a quantitative fire severity metric that can be used in conjunction with or instead of standard qualitative fire severity scores. We studied charcoals from a recent heathland wildfire in Carn Brea, Cornwall, UK, and assessed whether charcoal reflectance (Ro) can be linked to standard qualitative fire severity scores for the burned area. We found that charcoal reflectance was greater at sites along the burned area that had been scored as having a higher qualitative fire severity. However, there were clear instances where the quantitative charcoal reflectance measurements were able to better indicate damage and regrowth potential than qualitative scoring alone. We suggest measuring the reflectance of charcoals may not only be able to provide quantitative information about the spatial distribution of heat across a burned area post fire but that this approach is able to provide improvement to fire severity assessment approaches.

Additional keywords: burn severity, disturbance regimes, fire behaviour, moorland.

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Introduction

Fire has been suggested to have a complex role in the ecology of moorlands and heathlands (Davies *et al.* 2016). Recent debates regarding this role have focused on the use of fire as an ecological management tool (Davies *et al.* 2016). Such debates have centred around arguments based on the long-term historical use of fire in these settings versus building an understanding of how different fire disturbance regimes might influence the dynamic equilibrium that exists in moorland and heathland ecosystems (Davies *et al.* 2016). Some research has suggested that the presence of burning in these landscapes may have negative impacts (Brown *et al.* 2015), or argues that we lack the understanding that fire effects have on long-term carbon storage in these ecosystems (Douglas *et al.* 2015). Most moorland and heathland vegetation is, however, highly flammable and ignitions are common either via arson or accidental ignition. Recent examples of these types of ignitions include the large fires of summer 2018 on Saddleworth Moor and Winter Hill in the UK. As such, the impact of both managed and unmanaged fires requires building an additional understanding of the impact of different fire types on these ecosystems.

It has been suggested that the combination of the duration, degree and depth of heating at and below ground level will govern the impact of managed and unmanaged wildfires on moorlands or heathlands (under conditions where any peat beneath does not ignite) (Neary *et al.* 1999). For example, extended periods of heating above 50°C are likely to induce cambial kill in Calluna species, limiting resprouting (Davies *et al.* 2010).

Instrumented prescribed burns have been undertaken in such ecosystems and have provided valuable insight indicating that Calluna stand age and soil heating are both linked to the success of post-fire recovery (e.g. Davies *et al.* 2010). However, if we are to understand a range of management approaches and particularly compare them with unmanaged fires, post-fire methods are required because it is not easily practicable to fully instrument managed areas before a burn and even more difficult to achieve this in unmanaged fires. Novel tools that enable post-fire assessments of energy regimes are needed so that linkages between energy release and fire effects can be monitored.

Researchers have established that the structure of charcoal varies during creation owing to several different factors such as wood species, wood density and heating regime (Cohen-Ofri *et al.* 2006; Lowden and Hull 2013; Belcher *et al.* 2018). Experimental research has indicated that during the combustion process, charcoal transitions through various phases in which

Table 1. Fire severity field classification and severity scores; a simplified version of Ryan and Noste's (1985) original matrix that related fire severity to changes in soil organic matter and aboveground vegetation
This table has been modified for Carn Brea, after Keeley (2009)

Fire severity	Fire severity score	Description, modified for Carn Brea
Unburned	1	Plant parts green and unaltered, no direct effect from heat
Scorched	2	Unburned but heather and gorse exhibit leaf loss from radiated heat, fine fuels on ground charred
Light	3	Grass tussocks charred by radiated heat. Surface litter, mosses and herbs charred or consumed. Soil organic layer largely intact and charring limited to a few millimetre depth
Moderate or severe surface burn	4	Shrubs charred or consumed, base of tussock remaining. Fine dead twigs on soil surface consumed. Pre-fire soil organic layer largely consumed
Deep burning or crown fire	5	Exposed heather and gorse roots. Surface litter of all sizes and soil organic layer largely consumed. White ash deposition and charred organic matter to several centimetre depth

cells are eventually re-ordered to a more graphite-like structure (Cohen-Ofri *et al.* 2006; Belcher and Hudspith 2016). This re-ordering of cells alters the reflective properties of the charcoal, i.e. there is an increase in the quantifiable amount of light reflected from the surface of the charcoal as heating continues (Jones *et al.* 1991; Belcher and Hudspith 2016).

Research has shown that reflectance is in a state of constant change throughout the combustion process, where maximum charcoal reflectance is reached at the end of flaming combustion and the end of exposure to heating (Belcher and Hudspith 2016), where a strong positive relationship between increased total heat released during combustion and increased charcoal reflectance has been observed (Belcher *et al.* 2018). This seems highly relevant with respect to findings that the total energy released from fires can be linked to its impacts in this ecosystem type (Hamilton 2000). As such, charcoal's ability to retain information about the fire has the potential to make the study of charcoals a valuable resource in heathland and moorland fire research.

Many existing post-fire studies include qualitative approaches that assess fire or burn severity on the ground via qualitative visual evaluation of organic matter loss above ground and below ground (Keeley 2009). More recently, quantitative satellite-based burn severity assessment approaches are being used with varying results on such ecosystem types (e.g. Schepers *et al.* 2014). These approaches have been shown to be able to characterise burned compared with unburned areas of moorland and heathland; however, to remotely assess burn severity among the different vegetation types with confidence, some understanding of pre-fire vegetation distributions was required. However, neither of these approaches yield information that is inherently linked to the energy regime that formed them. For this reason, the present research has studied the potential use of charcoal reflectance in post-fire assessments as a tool to explore the variation in energy delivered by fires in moorlands and heathlands. Here, we suggest that areas that have burned and experienced a higher total energy release will produce charcoal that is more highly reflecting. We present findings of reflectance measurements in combination with a qualitative ground-based fire severity survey from a recent wildfire in a heathland fire at Carn Brea, Cornwall, UK. Our aim is to consider whether measuring charcoal reflectance may provide a useful tool for disentangling the effects of managed and unmanaged fires on moorland and heathland ecosystems.

Methods

Study site, sampling and monitoring

An unmanaged heathland fire in a region dominated by heather (*Calluna* sp.) and gorse (*Ulex europaeus*) occurred on 26 May 2015, burning 7 ha in Carn Brea, Cornwall, UK (50.2141°N, 5.2551°W) (BBC 2015) (Fig. S1, available as supplementary material to this paper). The heathland (maximum elevation of 252 m) is dominated by peat and gravelly acidic soils, and gorse and heather are the main fuel constituents; this mixed vegetation structure is homogeneous across the heathland (Natural England 2014). The patches of gorse and heather are intersected by several small streams and exposed granite outcrops (Natural England 2014). Charcoal samples and fire severity scores were taken 2 days post fire. A transect was taken across the axis of the fire scar, and the charcoal sampling locations documented using a Global Positioning System (GPS) device and photographs taken at each site. Samples were collected every ~1 m using a 1m x 1m quadrat and collecting charcoal within that area. The fire started at the bottom of the heathland and travelled uphill to where a footpath intersected the heathland, which appeared to have acted as a 'natural' fire break. Twelve sampling locations were identified along the transect and scored for fire severity following the descriptions shown in Table 1.

Nine months later, the ecological response to the 2015 fire at Carn Brea was assessed (March 2016). The vegetation regrowth was visually assessed and photographs taken at the 12 sampling locations at which the charcoal samples had been previously collected (Fig. 1).

Charcoal analyses

Charcoal was collected 2 days after the wildfire and dried in an oven at 40°C. The charcoal was embedded in cold-mounting epoxy resin following the approach of Belcher and Hudspith (2016). The charcoal blocks were studied in reflected light under a reflectance microscope, a Zeiss Axio-Scope A1 optical microscope, with a TIDAS-MSP 200 microspectrometer (SMCS Ltd, Baldock, UK), under oil with a refractive index of 1.514. In order to quantify the amount of light reflected back from the charcoal particles, the system was calibrated using three synthetic reflectance standards (cf. Belcher and Hudspith 2016). Samples were studied using an ×50 objective (with ×32 eyepiece magnification). A mixture of gorse and heather charcoal fragments were embedded in each block, ensuring a fair

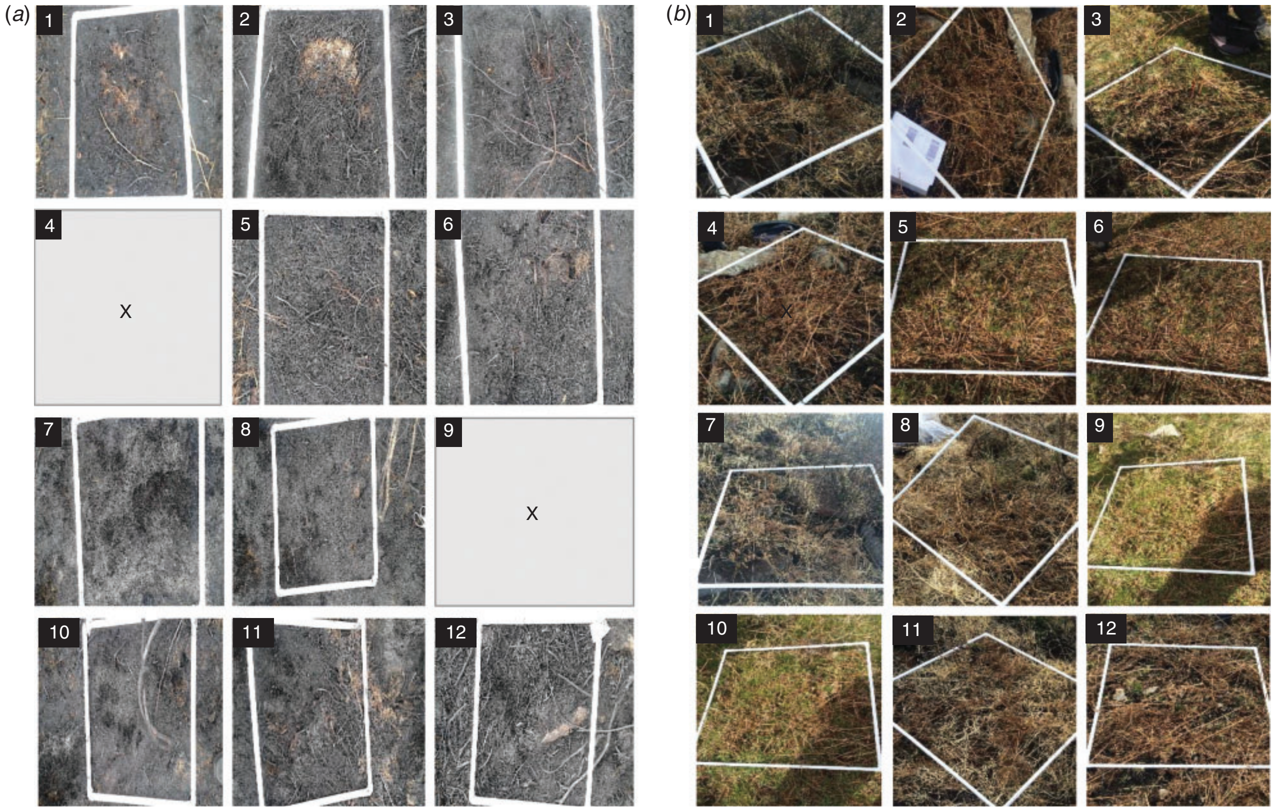

Fig. 1. Photographs of the sampling locations along the transect of the burn scar at Carn Brea. The left images (*a*) show the site 2 days after the wildfire; the right images are of the same locations 9 months later (*b*). Regrowth of grasses and mosses is evident in the images on the right with little bare soil visible. This is in contrast to the images on the left where the surface vegetation has evidently been consumed by the fire, leaving only roots and bare soil. There are no images available for Sites 4 and 9 in (*a*). (For scale the quadrat shown in the photographs is 1m x 1m).

representation of the fuel types in the analysis; 100 measurements of the cell wall reflectance were taken per resin block and five charcoal blocks analysed per site.

Results

Fire severity was found to be similar across the entire transect but was slightly higher in the area where a high fuel load of gorse dominated. Ten locations were classified as having a low fire severity (fire severity score 3), 'surface litter, mosses and herbs charred or consumed' (Keeley, 2009); the two remaining sampling locations were given a moderate or severe fire severity description (fire severity score 4), which includes 'all understorey plants charred or consumed, fine dead twigs on soil surface consumed, pre-fire soil organic layer largely consumed' (Keeley 2009) (Table 1). The locations along the burn scar that experienced higher fire severity were also found to yield charcoal with considerably higher reflectance when compared with the lower-severity sites, with median Ro% (measurement of charcoal reflectance) being >2% whereas all other sites (except site 12) yielded median reflectance of <1% (Fig. 2*a*). Images of the charcoal under the reflectance microscope are shown in Fig. S2, which indicates the range of reflectances found. Fig. 2*b* plots the density distributions of the charcoal reflectance values for each site compared with one another. It can be seen that the majority of sites have similar density distributions in reflectance values, with median reflectance values lower than 1. However, Site 12 can be seen to have higher density distributions with a large fraction >1 Ro% and Sites 7 and 8 have a large proportion of values >2 Ro%.

The lowest levels of regrowth were observed at Sites 7, 8 and 12 (compare Fig. 1*a* with 1*b*). Sites 7 and 8 were given qualitative severity scores of 4 whereas 12 was scored as 3. All three sites were found to exhibit median charcoal reflectance values of >1% (Fig. 1). Site 7 had experienced the lowest amount of regrowth after 9 months and yielded the highest reflectance of all sites. Median reflectance was 0.4 Ro% greater than the next most highly reflecting site (Site 8), which indicates Site 7 shows a 26% increase in median reflectance compared with Site 8. Both Sites 7 and 8 were given the same qualitative fire severity score despite this difference. The greatest regrowth was observed at Sites 9 and 10, followed by Sites 3, 5 and 6, all of which had median charcoal reflectance values of <1%. Site 1, despite having one of the lowest median charcoal reflectance values, appears to have experienced much slower regrowth. This site is at the base of the hill and is considerably rockier than the other sites; we anticipate that this has slowed its regrowth.

Discussion

Our analysis reveals that two sites (7 and 8) along the transect exhibited greater than double the measurable median charcoal

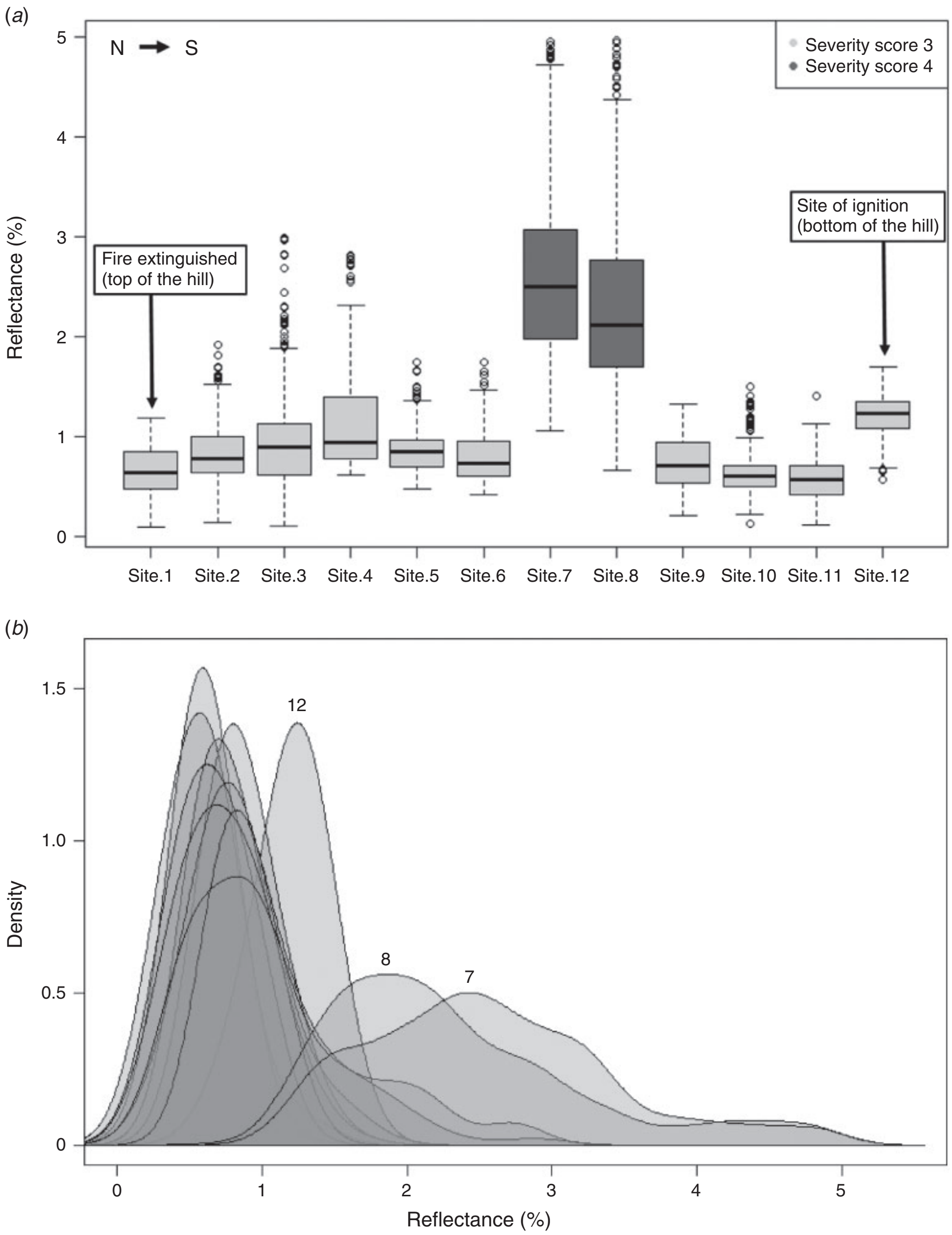

Fig. 2. Box plots (*a*), and density distribution plot (*b*) of the charcoal reflectance values for each site along the Carn Brea burn scar compared with one another. Sites 12, 8 and 7 are labelled as they are referred to in the text.

reflectance of the average of all other sites, and produced different reflectance distributions than all other sites (Fig. 2*b*). These two sites also had the highest qualitative fire severity score (4), and experienced significant shrub fuel consumption and loss of the soil organic layer. On revisiting Carn Brea the following year, regrowth at Sites 7 and 8 appeared to be slower than at the majority of the other sites, as would be expected from both the qualitative approach and reflectance-based quantitative approach. However, despite Sites 7 and 8 having the same qualitative score of 4, Site 7 exhibited a lower amount of regrowth than Site 8, and maintained several patches of exposed soil (compare Fig. 1*b* 7–8). Similarly, the regrowth at Site 12 appeared visually less dense than at Sites 2–6 and 9–11, which were all given the same qualitative score of severity 3. These observations would not have been predictable based on the qualitative fire severity assessment.

Sites 7 and 8 were qualitatively assessed as falling in the score of severity 4; however, Site 7 was observed to yield charcoals that are 26% more reflective than Site 8. Site 12 was the third highest-reflecting site, and like Sites 7 and 8, exhibited a different distribution in reflectance values when compared with Sites 1–6 and 9–11 (Fig. 2*b*). Again, despite this difference, Site 12 is qualitatively assessed as falling in the same severity score as Sites 1–6 and 9–11 (score 3). At Sites 7 and 12, the charcoal reflectance approach is shown to provide more information than qualitative scoring alone and has been able to successfully indicate enhanced impact by the fire at these sites when compared with the qualitative scoring categories.

Ecosystem impact has been linked with total energy output (Hamilton 2000) and the duration over which a site experienced high temperature (Gimeno-García *et al.* 2004), although others have suggested that it is variations in fire intensity that will link to consumption of aboveground biomass (and therefore link to fire severity) (Keeley 2009). Charcoal reflectance has been shown to positively correlate with total energy release in laboratory and field-scale wildland fire experiments (Belcher *et al.* 2018), and shows little relation to maximum fire intensity (Belcher and Hudspith 2016). This has led to the suggestion that studies of charcoal reflectance may have utility in determining the distribution of energy delivery across a burned area (Belcher *et al.* 2018). Although we do not have direct measurements of the fire itself, the two sites that experienced the highest pyrolysis intensity were observed to be areas of overgrown gorse that we suggest likely burned with a higher total energy release than the other areas along the transect. For example, the high fuel load may have resulted in the fire burning for a significant duration, such that increased total energy release in this area led to higher fire severity and generated higher charcoal reflectance. As such, our study of charcoal reflectance at Carn Brea implies that some sites along the transect experienced high total energy release and that these appeared to have been slower to start regrowth than sites with lower charcoal reflectances.

Owing to the linkage between charcoal reflectance and total energy release from fires, we suggest that reflectance measurements taken across transects of managed and unmanaged heathland and moorland fires may provide a useful post-burn metric for better assessing variations in the impact of managed burns compared with either natural or accidental fires in these ecosystems. Charcoal reflectance, therefore, may be able to provide information for developing appropriate prescribed fire actions to best manage these ecosystems to produce structurally diverse UK heathland and upland landscapes, as well as providing mitigation against the likelihood of extreme unmanaged fires occurring in the future.

Our findings also likely have consequences for understanding the influence of heathland fires on the carbon balance of these ecosystems, where both survival and regrowth of biomass influence the carbon balance through carbon accumulation following fire (Clay and Worrall 2011) and because charcoal itself can influence this balance (Santín *et al.* 2016). Recent research has been able to link the recalcitrance of charcoal to variations in charcoal reflectance (Belcher *et al.* 2018; Doerr *et al.* 2018) in both laboratory-generated charcoal and those formed by wildfires. In the present study, more highly reflecting charcoal has been shown to be more resistant to degradation and therefore able to add to longer-term carbon burial than less-reflecting charcoal. Therefore, although Sites 7 and 8 at Carn Brea may show slower regrowth, the higher reflectance measured at the sites suggest that these charcoals may be less biodegradable; potentially assisting in mitigating carbon losses. More research is required to consider the balance of carbon losses and gains (e.g. Santín *et al.* 2016).

In summary, the findings of this proof-of-concept study suggest that by taking measurements of charcoal reflectance, it may be possible to improve the resolution of fire severity assessments by providing quantitative data that is better able to indicate regrowth potential than broad qualitative fire severity scoring approaches alone. Additional studies should seek to undertake charcoal reflectance studies from wildland fires in a range of ecosystems and for larger sample sizes than presented here to fully determine if charcoal reflectance has the ability to move the discipline towards more quantitative fire severity assessment approaches.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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