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Research Note

Bark charcoal reflectance may have the potential to estimate the heat delivered to tree boles by wildland fires

Claire M. Belcher[A,E], *Stacey L. New*[A], *Michael R. Gallagher*[B], *Mark J. Grosvenor*[C], *Kenneth Clark*[B] and *Nicholas S. Skowronski*[D]

[A]wildFIRE Lab, Hatherly Laboratories, University of Exeter, Prince of Wales Road, Exeter, Devon, EX4 4PS, UK.
[B]USDA Forest Service, Northern Research Station, Silas Little Experimental Forest, 501 Four Mile Road, New Lisbon, NJ 08064, USA.
[C]Department of Geography, King's College London, Bush House, 30 Aldwych, London, WC2B 4BG, UK.
[D]USDA Forest Service, Northern Research Station, 180 Canfield Street, Morgantown, WV 26505, USA.
[E]Corresponding author. Email: c.belcher@exeter.ac.uk

Abstract. Currently, our ability to link wildland fire behaviour to fire effects is through the lens of fire severity assessments, because there are no ground-based post-fire metrics that are able to quantitatively capture aspects of heat transfer to plants. This presents a particular challenge when considering tree mortality linked to cambial damage, which can occur in both low-intensity surface fires through to high-intensity crown fires. Recent research suggests that measuring the amount of light reflected from charcoals produced by wildland fires will provide information about the energy flux that created the char. We created an experimental forest fire in which we had instrumented individual trees to record the energy delivered to the bark close to the base of the trees. We then assessed the bark charcoal reflectance of the same trees. We found that bark charcoal reflectance showed a strong positive correlation ($r^2 > 0.86, P = 0.0031$) with increasing duration of heating and the total energy delivered to the bark. We suggest that this may provide useful quantitative data that can be included in models or post-fire surveys to estimate tree mortality due to cambial kill.

Keywords: cambial kill, charcoal reflectance, energy flux, experimental fire, fire behaviour, fire severity, pitch pine, stem mortality.

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Introduction

Building an understanding of the effects of wildfires is critical to the management of both landscape fires and ecosystems. For plant material not consumed by the fire itself, it is the energy flux to plant parts that may determine mortality. For example, mortality in trees can be direct or indirect; direct mortality is caused by heat transfer to the crown, stem (bole) and root tissue by the fire, whereas indirect mortality can be from post-fire-induced drought or bark beetle attack (Dickinson and Johnson 2001). Damage to tree boles is determined by the time it takes for heat to transfer through the bark to the cambium of the tree, which is related to temperature and duration (i.e. energy flux). This can cause cambial necrosis (Dickinson and Johnson 2004; Michaletz and Johnson 2007) or increase the stem's vulnerability to cavitation, reducing hydraulic conductance because of heating of the xylem (Balfour and Midgley 2006; Michaletz *et al.* 2012; West *et al.* 2016). This means it is critical to understand the transfer of energy to plants; however, quantifying energy release and energy transfer during wildfires is complex (Kremens *et al.* 2012) and further complicated by the fact that in most cases, we only have access to the post-fire environment from which to assess potential damage, therefore proxies for energy transfer are required.

Recent research has indicated that the light reflecting properties of charcoals, as measured using reflectance microscopy systems (Belcher and Hudspith 2016; Belcher *et al.* 2018), correlate to measures of energy release and may improve upon qualitative fire severity assessments (New *et al.* 2018). Bench-scale laboratory tests using a cone calorimeter, known heat flux (kW m^{-2}) and piloted ignition of *Thuja plicata* wood have shown that increasing charcoal reflectance and charring depth positively correlates with increasing total heat release (Belcher *et al.* 2018). This finding was further supported by field-scale experiments, where blocks of *T. plicata* were attached to thermocouples placed on the ground ahead of fires (Belcher *et al.* 2018; Doerr *et al.* 2018). The reflectance values of the charred *T. plicata* samples were shown to positively correlate with the integrated area (>300°C) under the thermocouple curves and the duration of heating, suggesting that final charcoal reflectance and its variation between different fires is a balance between the heat release rate (kWm^{-2}, fire intensity) and the duration over which the material is exposed to flaming. Moreover, surface charcoal samples generated by surface fires have been found to have lower reflectance than those formed by crown fires (Belcher *et al.* 2018; Doerr *et al.* 2018; Roos and Scott 2018). If this approach can be further developed it has the potential to take observations of charring from their current subjective usage (e.g. Ryan 1982; Hood *et al.* 2008) into the quantitative arena, enabling relatively rapid assessment of the heat transfer to plants during both prescribed and wildland fires.

Here we sought to quantify the effect of incident heat flux on the formation of bark charcoal reflectance of standing live trees subjected to a large-scale experimental wildfire. We anticipated that variations in aspects of fire intensity and/or duration of heating would link to variations in the reflectance of the charcoals produced. If this hypothesis is correct, then the charcoal reflectance approach could be developed into a ground-based quantitative proxy that can be used to explain tree mortality patterns across burned areas.

Materials and methods

Site description

Our experiment was undertaken in the New Jersey Conservation Foundation's Franklin Parker Preserve, located in Burlington County, New Jersey, USA, within the New Jersey Pinelands National Reserve. The prescribed burn unit known as Parker Preserve North covered 15.4 ha and was burned during the morning of 23 March 2017 (Fig. 1). The site has very little slope, as is typical in this landscape. Prior to the experimental fire, the unit had not been burned or managed since a major wildfire in the spring of 1954. The forest overstory was dominated by pitch pine (*Pinus rigida* Mill.), a fire-adapted species, while the understory comprised mixed ericaceous shrubs, shrub oaks and associated species, such as lowbush blueberry (*Vaccinium palladum* Aiton and *angustifolium* Aiton), black huckleberry (*Gaylussacia baccata* (Wangenh.) K. Koch.), scrub oak (*Quercus ilicifolia* Wangenh.), blackjack oak (*Q. marilandica* Muenchh.) and inkberry holly (*Ilex glabra* (L.) A. Gray). This vegetation is representative of pitch pine-dominated upland forests within this landscape. Wildfires and prescribed fires have historically played an important role in this landscape and presently affect ~10 000 ha annually with a mix of severities (Skowronski *et al.* 2020).

The fire was conducted by the New Jersey Forest Fire Service and undertaken in collaboration with the US Forest Service. Meteorological data were collected on the western, upwind side and logged to a Campbell Scientific CR3000 data logger with a 1-min integration time. Wind data were collected with a wind vane (05013-5, R.M. Young Co., Traverse City, MI, USA), averaging 2.54 m s^{-1} from the north with peak gusts of 5.0–5.7 m s^{-1}, while air temperature and relative humidity data were collected with an HMP45 temperature and relative humidity sensor (Vaisala, Inc., Woburn, MA, USA) and averaged 0.3°C and 24%, respectively. These conditions fall within the general range of conditions under which prescribed burns are conducted on this landscape (Clark *et al.* 2020). A single linear ignition was used to light the head fire with the wind, using drip torches along the edge of the plot that trends south-west-north-east as marked on (Fig. 1). The surface head fire took ~15 min to completely spread across the burn unit, with torching of some

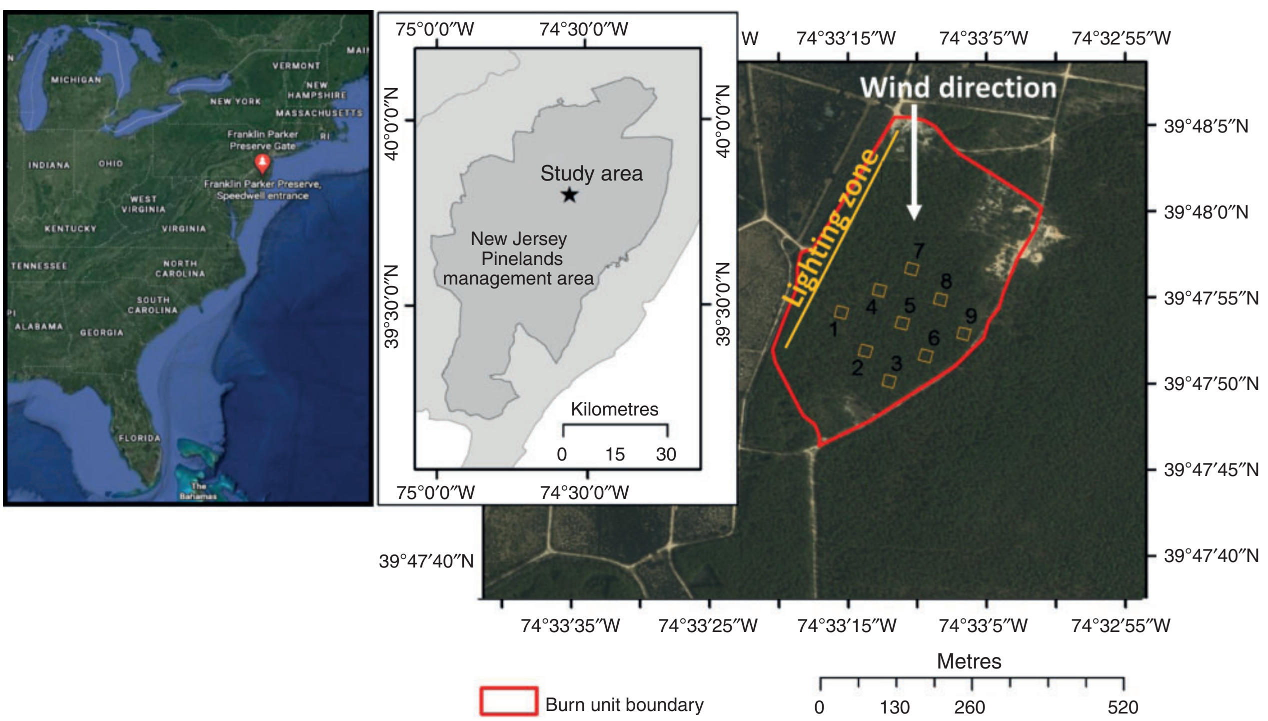

Fig. 1. Location of the burn plot in the Parker Preserve, New Jersey, USA, and the locations of subsites within the experimental plot.

trees, and stopped when it reached a large adjacent burned area of >400 ha that had been treated with prescribed fire earlier in the month. Mean char heights on tree trunks were 5.35 m (range 3.1–6 m) at the nine subsites and canopy cover loss ranged from just 1% through to 30%.

Monitoring approach and equipment

Nine subsites within the burn area were identified and a single tree of similar height and diameter at breast height (DBH) selected for instrumenting at each site. We selected trees of similar DBH (range 24–33 cm, mean 28.5 cm diameter) so that bark thickness and bark plate size would be similar for each specimen; as DBH has been linked to mortality in a range of species (Hood *et al.* 2018). The nine subsites are indicated on (Fig. 1) and formed a grid across the plot creating three transects of three points; each subsite was located ~75 m from the next subsite. Photographs were taken before the burn at each subsite in all directions. The subsites were then re-photographed following the fire, allowing comparison of images before and after the fire (Fig. 2).

Type K–310 Stainless Steel Sheath 1.00 mm diameter × 1500 mm long thermocouples were utilised (supplied by TC direct, Uxbridge, UK) to identify the arrival time of the fireline at each subsite and monitor the transient rise and decline in temperature as the fireline passed and heating diminished. The thermocouples were placed on the lower parts of the tree because cambial injury often occurs close to the base of trees due to heating from the consumption of litter and duff (Hood *et al.* 2008). The thermocouples were attached to Testo 176 T4 temperature battery-powered LCD display data loggers (Testo, Alton, UK). The data loggers were wrapped in foil and buried in sealed plastic bags ~20 cm below the surface, to prevent them from being damaged in the fire. All thermocouple wires were buried as deep as possible and wrapped in foil so that only the tips were exposed to the fire. None were damaged in the fire.

Post-burn sampling and preparation of charcoals

A set of charred bark samples from each location was collected at breast height, as well as the charred bark directly attached to the thermocouples, immediately after the fire. The charred bark plates were broken off carefully with a knife so that large (minimum 4 × 2 cm) pieces of charred remained intact and orientated. The charred bark that related exactly to the thermocouples at each subsite was lightly ground and an aliquot added to a resin block and then prepared as described in Belcher and Hudspith (2016). Three samples were analysed per subsite and 30 reflectance measurements taken per sample (90 measurements per subsite/tree). The samples were lightly ground as opposed to being left intact (as in Belcher and Hudspith 2016) so that the most highly reflecting uppermost char layers were not

Fig. 2. Images of each monitored location before and after the burn; all photographs are taken facing approximately equal directions.

preferentially lost in the polishing process. Polishing the upper surface of an intact bark sample will tend to remove the highest reflecting part (the part of key interest). However, if the sample is lightly ground, added to a well in a resin block and then polished there is a greater chance of the highest reflectance (i.e. the surface that was in direct contact with the fireline being preserved and measurable as individual fragments). This light grinding approach preserved the cellular structure of the particles but served to fragment the otherwise large bark plates (Fig. S1, Supplementary Material). Particles >120 µm in size were measured (examples are shown in Fig. S1). The 30 most highly reflecting particles were measured per block ($n = 90$ for each subsite), with the aim of capturing the reflectance produced from the same surface that our thermocouples were linked to (i.e. the bark surface).

Statistical analysis of correlations between the measurements taken and charcoal reflectance (Ro%) were undertaken using the PAST statistics package (Hammer *et al.* 2001) by running an ANOVA test for linearity. We report r^2 and P values for each relationship.

Results and discussion

The visual changes in each subsite from pre-burn to immediately post-burn (Fig. 2) showed that most of the surface fuels were consumed during the burn. The trunks of pitch pine were considerably charred and observed to carry the fire up to the crowns, with the fire climbing the gaps between bark plates. Char heights ranged from 3.1 to 6 m (mean 5.36 m) across the nine subsites and peak temperatures at the bark's surface ranged from ~650°C to 1008°C (mean 839°C). These observed temperatures were remarkably consistent with those observed in the air space between trees during two previous, independent, studies that reported peak values at similar measurement heights between 664°C and 1017°C during head fires in the same ecosystem type (Thomas *et al.* 2017; Mueller *et al.* 2018). The longest duration of heating measured was ~11 min and the shortest was 4 min (mean 7.2 min). The mean rate of spread across the nine subsites was 0.48 m s^{-1}.

We found a strong positive correlation between the integrated area under thermocouple curves and mean charcoal reflectance ($r^2 = 0.860$, $P = 0.0031$, Fig. 3*a*). A similarly strong positive correlation was indicated between duration of heating >70°C (calculated from thermocouple traces) and mean charcoal reflectance ($r^2 = 0.885$, $P = 0.0002$, Fig. 3*b*). No significant relationship was found between maximum bark surface temperature and maximum charcoal reflectance ($r^2 = 0.012$, Fig. 3*c*) and mean bark temperature (>70°C) and mean charcoal reflectance ($r^2 = 0.099$, Fig. 3*d*).

Previous field-based research indicated that charcoal reflectance varies between surface and crown fires; surface fires have been shown to produce charcoals of lower reflectance than those formed during crown fires (Belcher *et al.* 2018; Roos and Scott 2018). In both of those studies, charcoal reflectance was measured from charcoals formed and collected on the ground. The mean charcoal reflectance values found for crown fires in south-western US dry mixed conifer and ponderosa pine (*Pinus ponderosa*) forest by Roos and Scott (2018) were relatively low – mean 0.883%, which contrasts to those measured by

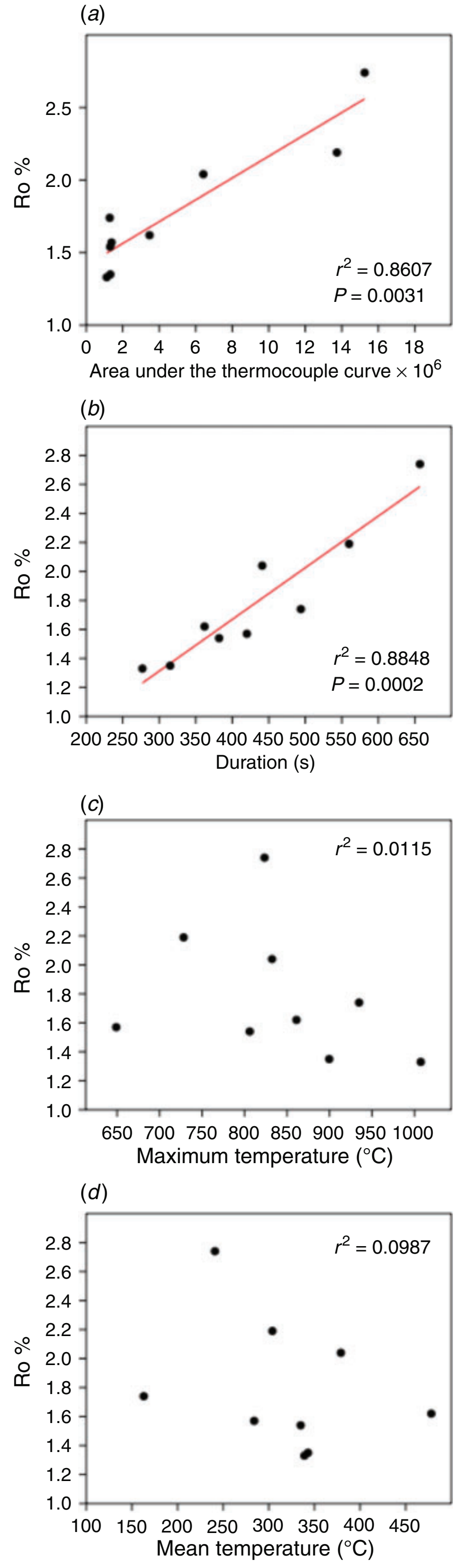

Fig. 3. Parameters measured at each subsite in the experimental wildland fire at the Parker Preserve New Jersey, USA, and their relationship to charcoal reflectance (Ro%). (*a*) Integrated area under the thermocouple (>70°C) × 10^6; (*b*) duration of heating (>70°C); (*c*) maximum temperature measured (°C); and (*d*) mean temperature (°C). Linear regression correlation strength is noted in the r^2 and P values for each correlation (using an ANOVA test).

Belcher *et al.* (2018) for a crown fire, in Canada, in a mature black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) stand where the charcoal reflectance was 1.55%. The mean charcoal reflectance measured at each subsite in our New Jersey study ranged from 1.33 (subsite 2) to 2.74% (subsite 9); this is a similar range (1.35–2.27% mean) to that measured by Belcher *et al.* (2018) in a black spruce–jack pine crown fire. The integrated area under the thermocouple curves (°C s) in the same fire was also found to be greater for the crown fire than the surface fire studied.

Tree mortality following fires depends on the level of injury to the crown, the bole and the roots. Cambial injury due to heat is strongly influenced by heat duration and bark thickness (Ryan and Frandsen 1991), as well the thermal properties of the species' bark (van Mantgem and Schwartz 2003). For example, tree mortality has been linked to the heating duration of tree boles (Keeley and McGinnis 2007) and stem heating models, such as FireStem, have been developed to predict cambium death from surface fires (e.g. Jones *et al.* 2004, 2006). The FireStem model(s) require the duration of the heat pulse as an input to predict cambial cell mortality (Jones *et al.* 2004, 2006; Chatziefstratiou *et al.* 2013). Our results indicated not only a strong positive correlation between increasing bark charcoal reflectance and the integrated area under the thermocouple curve (which captures the variation in energy regime over time) ($r^2 = 0.860$; Fig. 3*a*), but also a strong positive correlation between increasing bark charcoal reflectance with increasing duration of heating ($r^2 = 0.885$; Fig. 3*b*). In our experiments we found that for pitch pine bark, a mean surface charcoal reflectance value of 2.74% (the maximum mean measured in our experimental fire) would imply that heating >70°C occurred for ~665 s (11 min) which, in a large range of species, would be sufficient to cause cambial kill. By gathering more data to build on that presented in (Fig. 3*a*, *b*) it may be possible to generate calibration curves that could be used for given species.

The degree of charring of bark has long been debated for its utility to derive forms of empirical data from post-fire landscapes, particularly in regard to determination of the likelihood of mortality in tree boles. For example, Ryan (1982) proposed a scheme that considered the degree of bark charring near the base of tree boles following fires, which has subsequently been tested by others (e.g. Hood *et al.* 2008). Such approaches are subjective observational techniques, which are open to different interpretations. However, charcoal reflectance is a non-subjective measure that produces quantitative values and provides more detail than can be observed with the naked eye. Therefore, it has considerable advantage over qualitative approaches because it provides a simple quantification of the reflectance of light, which relates to a physical change in the structure of the cells of the bark due to heating.

Under a reflected light microscope these physical changes are observed as changes in the colour of the cells from their natural pre-burn state (Fig. S2a, Supplementary Material) and there is a progressive darkening of colour to dark brown as heating is increased (Fig. S2b, Supplementary Material). Between these states the cells maintain their cell wall layering. Once the heating of the sample exposes the cells to a temperature of ~325°C they begin to char and the cell wall layering is lost (Fig. S2c, d, Supplementary Material). Throughout the transition from virgin bark to the early phase of charring polymers such as cellulose and hemicellulose are lost (Drysdale 2011); as charring proceeds lignocellulosic structures start to decline in abundance (Knicker *et al.* 2010; Ascough *et al.* 2010). It has been shown that increasing duration of heating leads to an increasing loss of lignin from the char (Belcher *et al.* 2018). As energy transfer continues, the reactive lignocellulosic substances will eventually be entirely lost and only polyaromatic compounds will remain. As the heating continues the ordering of the molecular structure of polyaromatic microcrystalline domains increases and it is this increase in the ordering of the molecular structure that causes greater reflectance of light from the char (Ascough *et al.* 2010; Belcher *et al.* 2018). Under reflected light this is observed as a shift from brown to dark grey to bright grey colour of the cells (Fig. S2b–e, Supplementary Material); where the amount of light reflected back from the charcoal (grey *v.* lighter brighter grey) is dependent on the extent of graphite-like phases within the molecular structure of charcoal that increase as the internal temperature rises (Cohen Ofri *et al.* 2006).

Bark char is unique in its duration of evidence; char remains in tree stems and branches for many years post fire and is the most persistent and prominent indicator of wildland fire (Hood *et al.* 2018). Our research indicates that charring can be used beyond the subjective arbitrary categorisation of less charred, more charred and deeply charred to assess damage to trees. Here we have shown that charcoal reflectance provides a quantitative measurement of the degree of charring that is not possible to estimate visually but is underlain by both changes in the chemical and physical properties of the material and the evolving response to the energy flux applied. Therefore, we believe that our research indicates that charcoal reflectance is the first quantitative tool that we can use to understand the energy transfer to plants using one of the most abundantly available products of fire.

We explored the fire–reflectance relationship in just one (strongly fire-adapted) species (*P. rigida*), which has thick-flaky bark that protects it from fire damage and varies in thickness with tree diameter and height (Gallagher 2017). Thus the mature individual trees that we studied meet the assumption for having maximally thick bark. Thermal conductivity has been shown to relate to its specific gravity (oven-dry bark), as well as the moisture content (Simpson and TenWolde 1999); others have related it to the density of dry bark and moisture and temperature (Martin 1963). The density of bark and wood varies considerably among species and is influenced by moisture content. Woods of higher bulk density generate more highly reflecting charcoals when heated for the same duration (Belcher *et al.* 2018) and where higher moisture content leads to lower charcoal reflectance (Belcher and Hudspith 2016). Additional experiments are required to link energy changes and duration of heating into the bark with measurements of the variation in reflectance throughout the thickness of the bark (not just at the surface as we monitored in the present study). This should allow the heat transferred through the bark to the cambium to be quantified, improving further on the data presented here.

We conclude that in order to develop the charcoal reflectance approach for common usage it will need to calibrated for a range of species, bark densities and moisture contents and for dead and live fuels (e.g. Talucci *et al.* 2020) before calibration curves/functions can be produced and used to estimate the duration of heating and total energy delivered to tree boles of key species. If such calibration curves can, in time, be produced then measurements of charcoal reflectance post-burn could be made to (1) provide information on duration of heating of tree boles as input data for mortality models (e.g. FireStem) and (2) estimate burn durations either as an average over the burned area or for individual trees of interest in post-fire surveys. Hence, the charcoal reflectance–duration relationship could be used to provide quantitative data with which to improve estimates of mortality in response to prescribed fires, in the pre- and post-planning stages or following wildland fires for post-fire salvage (Hood and Lutes 2017).

Conflicts of interest

The authors declare no conflicts of interest.

Declaration of funding

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