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A comparison of charcoal reflectance between crown and surface fire contexts in dry south-west USA forests

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Abstract. The historical and modern importance of crown fires in ponderosa pine and dry mixed-conifer forests of the south-west USA has been much debated. The microscopic reflectance of charcoal in polished blocks under oil shows promise as a semiquantitative proxy for fire severity using charcoal from post-fire landscapes. We measured the reflectance of 33 modern charcoal samples to evaluate (1) whether charcoal reflectance can distinguish between crown fires and surface fires in these forests; and (2) whether surface fires with masticated fuels burn with severities similar to surface fires in grass, litter and duff fuels. The charcoal analysed was primarily collected after wildland fires under two different conditions: (l) wildfires with moderate to high severity and crown fire behaviour ($n = 17$), and (2) prescribed fires with low to moderate severity but no crown fire behaviour ($n = 16$). Statistical analysis indicates that charcoal reflectance produced in crown fires significantly differs from surface fire charcoal, particularly surface fire charcoal formed in grass, duff and litter fuels. However, charcoal produced from surface fires in masticated fuels is indistinguishable from crown fire charcoal, suggesting that fires in areas that have experienced *in situ* mastication may have soil impacts similar to crown fires.

Additional keywords: charcoal analysis, dry mixed-conifer forests, ponderosa pine forests.

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Introduction

The historical and modern ecological importance of crown fires in ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer forests of the south-west USA has been much debated. Tree-ring studies suggest that these forests experienced frequent (once or twice per decade) surface fires for at least 5 centuries before widespread Anglo settlement at the end of the 19th century (Swetnam and Baisan 1996; Touchan *et al.* 1996; Fulé *et al.* 1997; Grissino Mayer and Swetnam 2000; Allen *et al.* 2002; Swetnam and Baisan 2003; Falk *et al.* 2011; Swetnam *et al.* 2016). From this perspective, crown fires were limited in size, and the evolutionary ecology for the dominant species in these contexts, *Pinus ponderosa*, was shaped by frequent, low-severity surface fires (Covington and Moore 1994; Allen *et al.* 2002; Covington 2003; Covington and Vosick 2003). In this context, the large (>10 000 ha), recent crown fires are unusual and require mitigating action to conserve this forest type (Fulé *et al.* 1997; Swetnam *et al.* 1999; Covington *et al.* 2001; Allen *et al.* 2002; Fule *et al.* 2006).

By contrast, a minority of scholars suggest that crown fires are systematically underrepresented in the tree-ring record and, therefore, contemporary fire behaviour is within the range of historical variability (Baker and Ehle 2001; Odion *et al.* 2014). This perspective is not well supported in tree-ring or other paleofire records for the region (Fulé *et al.* 2014), although the role of large (>1000 ha) crown fires at millennial or multimillennial scales (Whitlock *et al.* 2010) is largely unknown. However, small (<400 ha) crown fires in recent millennia are supported by dendrochronology of shrubfield patches (Guiterman *et al.* 2017), stand-age reconstructions (Bigio *et al.* 2016) and alluvial records (Fitch and Meyer 2016; Bigio *et al.* 2017). Furthermore, the last century has witnessed changes in the composition of surface fuels in dry south-western forests. Prior to the 20th century, these forests had open canopies and a dense understorey of grasses and forbs (Covington and Moore 1994). With overgrazing and fire suppression, understorey grasses have largely given way to dense litter layers of needles and cones. In the absence of surface fires, young conifers filled in the space previously occupied by grasses, creating the altered canopy fuel structure that is so important for facilitating modern crown fires. More recently, this infilling has been mitigated by thinning young trees and relocating them to piles for burning, or masticating the young trees and spreading the shredded wood *in situ* followed by prescribed burning (Stephens and Moghaddas 2005; Reiner *et al.* 2009; Knapp *et al.* 2011). Masticating small-diameter trees to restore presettlement stand structures and fire behaviour is controversial, in that the shredded and chipped woody fuels left on the surface have no analogue in presettlement fuel loads (Kane *et al.* 2009), tend to flame and smoulder for long durations (Kreye *et al.* 2014) and may elevate fire severity (i.e. soil heating) even with surface fire behaviour (e.g. Busse *et al.* 2005).

Charcoal reflectance is an emerging field of research that has promise for contributing to both of the aforementioned debates on the historical role of crown fires and the impact of masticated fuels on fire severity (Jones *et al.* 1991; Scott and Jones 1994; Scott and Glasspool 2005; McParland *et al.* 2007; McParland *et al.* 2009*a*, 2009*b*, 2010; Ascough *et al.* 2010; Hudspith *et al.* 2014, 2015, 2017; Belcher and Hudspith 2016; Veal *et al.* 2016; Hudspith and Belcher 2017; Mastrolonardo *et al.* 2017). Charcoal is the product of incomplete combustion of organic matter. In pyrolysis, organic molecules in the cell walls are reorganised into aromatic structures that increase in size with temperature (Cohen-Ofri *et al.* 2006). These aromatic molecular structures grant charcoal one of its distinguishing qualities, that broken surfaces reflect light (Scott 2010). Early research demonstrated that when embedded in resin, polished and examined with a reflectance microscope under oil, the proportion of visible light reflected from cell walls was predictably related to the temperature of charcoal formation in the absence of oxygen (Scott 1989, 2000; Scott and Jones 1991). Further research indicated that the duration of exposure to a particular pyrolysis temperature also influenced the final reflectance value (Scott and Glasspool 2005). Experimentally produced charcoal was used to generate calibration curves by which charcoal reflectance measurements were converted to minimum pyrolysis temperatures, meaning the minimum temperature that would have been needed to create a particular reflectance measurement (McParland *et al.* 2009*b*; Hudspith *et al.* 2015; Veal *et al.* 2016).

More recent experiments, published in this journal, suggest that these earlier studies overlooked one key component of wildfire behaviour – flaming combustion (Belcher and Hudspith 2016). Belcher and Hudspith (2016) document that peak reflectance is actually achieved at the end of flaming combustion and not at peak heat release. Furthermore, fuel moisture content seems to affect the reflectance values achieved in open flaming conditions, with higher fuel moistures reducing peak reflectance values. In their assessment, they suggest that charcoal reflectance may be best treated as a semiquantitative proxy for fire severity (Belcher and Hudspith 2016, p. 779), rather than pyrolysis intensity (cf. Hudspith *et al.* 2015). Previous opportunistic sampling of charcoal from different fire behaviour (crown vs surface fire) and different fire severities suggests that it may be possible to distinguish these contexts on the basis of mean charcoal reflectance of collected samples (Scott and Jones 1994; McParland *et al.* 2009*a*; Hudspith *et al.* 2014, 2015). However, these samples were often from different vegetation and fuel settings, rather than comparing charcoal reflectance from different fire behaviour types from within the same climatic and ecological context.

Here, we analyse surface charcoal from different fire behaviour types (crown vs surface) in dry south-western US conifer forests (ponderosa pine and dry mixed-conifer forests dominated by *Pinus ponderosa* Douglas ex C.Lawson and *Pseudotsuga menziesii* (Mirb.) Franco, see Fig. 1) (Brown 1994). Charcoal production in these forests occurs primarily in the surface fuels regardless of fire behaviour (Scott 2010, pp. 15–17). With charcoal collected from two surface fires and two crown fires, we generated charcoal reflectance measurements for 33 samples from these contexts. One of these surface fire contexts included burning in masticated fuels. Our results suggest that surface and crown fires can be distinguished on a sample-by-sample comparison of charcoal reflectance properties. Furthermore, the reflectance properties of surface fires in masticated fuels are indistinguishable from crown fires in natural fuels, suggesting that masticated fuels may facilitate surface fire behaviour while enhancing fire severity experienced by the soil. We follow Keeley (2009) and others (DeBano *et al.* 1998, p. 11; Safford *et al.* 2008) to define fire severity as a description of soil impacts, often assessed through the consumption of above- and belowground organic matter and directly related to the temperature and duration of soil heating, something to which charcoal reflectance is well positioned to contribute (Belcher and Hudspith 2016).

Materials and methods

We collected charcoal from the ground surface of four different forest fires in the southern Jemez Mountains of northern New Mexico (Fig. 1). All sampling locations were situated between 2260 and 2820 m elevation. The nearby weather station at Jemez Springs at 1890 m elevation reports an average annual temperature of 11.3°C and annual mean precipitation of 442 mm. Sample locations from the Las Conchas, Thompson Ridge and San Juan prescribed (Rx) fires had not burned in the 20th century, according to modern fire atlas records. Four sample locations from Chaparral Rx were burned in either 1989 (Chaparral Rx (CPRx) 5 and 6) or 1996 (CPRx 1 and 2). Seven of the San Juan Rx samples were collected from the Monument Canyon Research Natural Area (MCRNA), which has one of the best-replicated stand-level tree-ring-based fire histories in the south-west USA. Fire-scar records from MCRNA indicate that the area witnessed surface fires once or twice per decade for at least 3 centuries before fire suppression during the 20th century (Falk 2004; Falk *et al.* 2007, 2011; Liebmann *et al.* 2016; Swetnam *et al.* 2016). Fire-scar samples from throughout the Jemez Mountains suggest a similar fire history across dry conifer forests in the region (Touchan *et al.* 1996; Falk *et al.* 2007; Swetnam *et al.* 2016). There is no evidence for large crown fires in these forest types over recent centuries, although dendrochronology of persistent shrubfields (Guiterman *et al.* 2017) and fire-related sedimentation suggest a role for small crown fires at millennial timescales (Fitch and Meyer 2016).

Charcoal samples were collected opportunistically near roads (~50–200 m), in settings that were safe to traverse in post-fire environments (Table 1). We collected samples from four burn areas with different fire behaviour (surface vs crown) and different pre-fire fuel conditions (masticated and natural fuels; Fig. 2). For three burn areas (Las Conchas (LCN), Thompson Ridge (TRF), and Chaparral Rx (CPRx)), at least two localities were sampled to include some potential variability in fire conditions within the burns. For the San Juan prescribed burn (SJRx), all samples were collected along an approximately 1.6 km long transect to capture within-fire variability (Fig. 1;

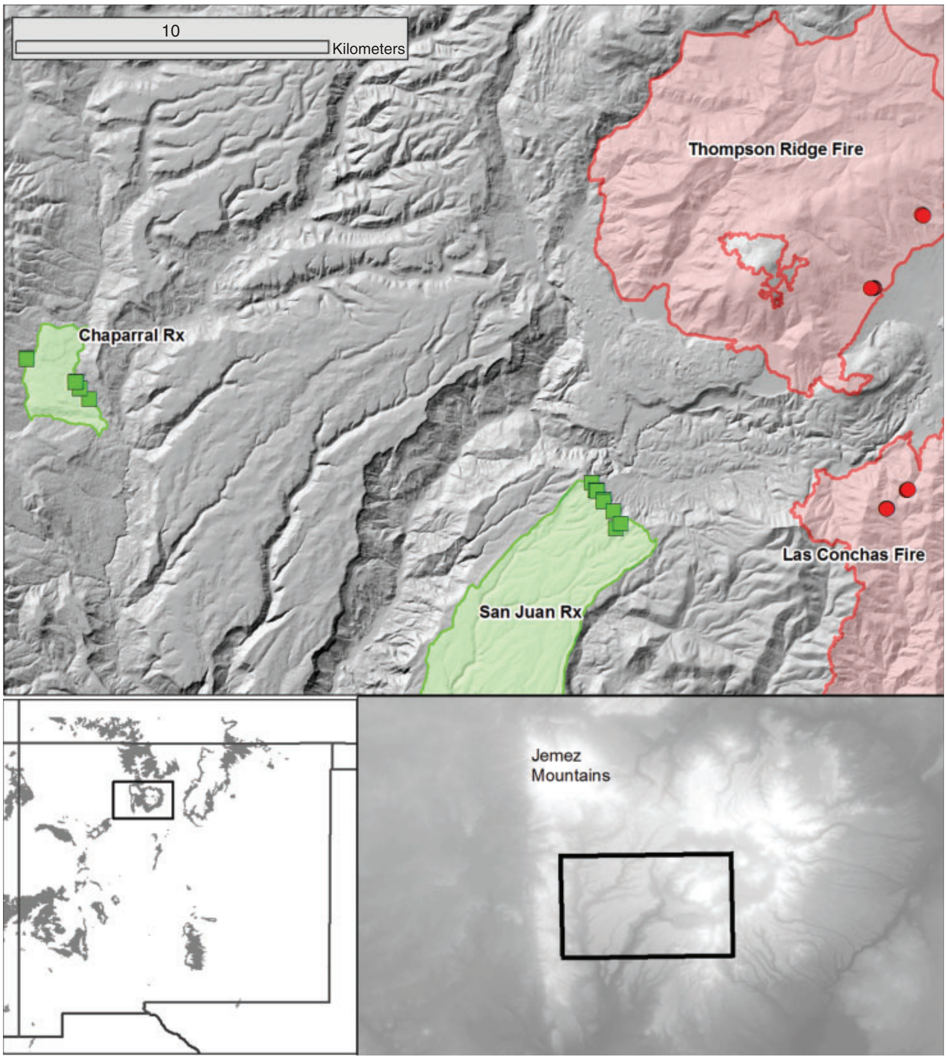

Fig. 1. Map of charcoal collection locations in the context of the four forest fires. Circles are for crown fire samples. Squares are for surface fire samples. Grey areas in the regional inset illustrate the distribution of dry forests in New Mexico (source: Brown 1994). Red polygons in the study area indicate the boundaries of the two crown fires studied. Green polygons in the study area indicate the boundaries of the two prescribed burns studied.

Table 1. Summary of charcoal sample collection sites and the fires that produced them

Fire severity was assigned from BAER (Burn Area Emergency Rehabilitation) mapping for Thompson Ridge and Las Conchas fires. The local consumption of organic matter was used to determine fire severity for the Chaparral and San Juan prescribed burns

Fire	Fire type	Fuel and vegetation type	Collection date	Number of samples	Fire severity classes sampled	Abbreviation
Thompson Ridge fire (June 2013)	Crown fire	Natural dry mixed conifer	August 2013	9	Moderate	TRF
Chaparral prescribed burn (October 2012)	Surface fire	Natural ponderosa pine	May 2013	6	Low	CPRx
San Juan prescribed burn (October 2012)	Surface fire	Natural and masticated ponderosa pine	May 2013	10	Low and moderate	SJRx
Las Conchas fire (June–July 2011)	Crown fire	Natural dry mixed conifer	May 2013	8	Low, moderate and high	LCN

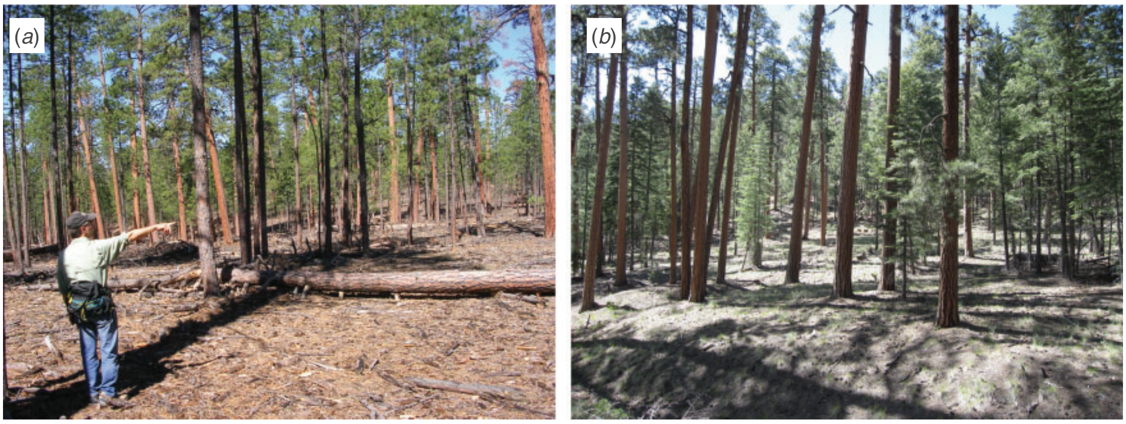

Fig. 2. Photographs illustrating different pre-fire fuel and vegetation conditions sampled in the study: masticated fuels (*a*); and grass, duff and litter fuels (*b*). Our surface fire contexts burned in both fuel conditions, whereas our crown fire contexts burned in (*b*).

Table 1). Multiple sample collection spots were chosen at each locality to assess within-locality replicability. All sample collection spots were chosen to identify level or gently sloping terrain where post-fire erosion and reworking of surface charcoal would be minimised. Samples were collected from soil surfaces that appeared to retain char and ash, although some deflation and erosion could not be ruled out on older samples (LCN) and was clearly evident on some locally reworked material in the most recent fire (TRF). As one would expect, the summer-burning crown fires (LCN and TRF) burned with higher maximum air temperatures (>30°C) and lower minimum relative humidity (~6% RH) than the autumn-burning prescribed fires (SJRx and CPRx; <20°C and ~11–16% RH). Dead fuel moistures were similar between the crown fires and surface fires (~6% for 1000-h fuels).

There is some evidence that higher-reflecting charcoal is more fragmentary (Nichols *et al.* 2000; Scott 2010) and that charcoal particles of different reflectance values may segregate by size (Mastrolonardo *et al.* 2017); therefore, our collection effort was designed to collect and preserve charcoal of all size fractions *in situ.* Each sampling locale was photographed before tapping PVC down-piping or junction boxes into the surface of the collection site, packing them with tissue paper, excavating them, and wrapping them tightly with plastic wrap (Goldberg and Macphail 2003). Bulk samples of loose char and ash were collected during the excavation process for spectroscopic analysis (not reported here). The 33 undisturbed samples were oven-dried and embedded in polyester resin at the Geoarchaeology Laboratory at Southern Methodist University. Resin blocks were cut to expose a profile of the charcoal and ash deposit above the mineral soil and this exposed profile was polished at the Department of Earth Sciences at Royal Holloway, University of London, for analysis.

Polished blocks were mounted on a glass slide and levelled for reflectance measurement (hereinafter 'measurement') on a Tidas MSP200 photometry system attached to a Leica DM microscope with oil immersion objectives and a mechanical stage (SMCS Ltd., Baldock, Hertfordshire, SG7 6QQ, UK). These measurements are referred to as 'random reflectance' because we take the measurements of reflectance at whatever orientation the charcoal particles are encountered, and they are reported as percentage reflectance under oil (%Ro). The instrument was calibrated with measurements of standards at least once every 5 h. Reflectance standards included spinel (%Ro = 0.393), YAG (yttrium aluminium garnet; %Ro = 0.929), GGG (gadolinium gallium garnet; %Ro = 1.7486), cubic zirconium (%Ro = 3.188) and silicon carbide (%Ro = 7.506). Each sample was traversed at 400× magnification in transects beginning near the top of the profile of the charcoal and ash deposits. Cell walls of charred plant tissues and charred faecal pellets that were observable at the surface of the block (Fig. 3) and of sufficient thickness for measurement (>2 μm) were measured until a minimum of 100 total measurements had been made for each sample (~60+ charcoal particles per sample). This generally meant traversing the upper 2–3 cm of the sample profile. Larger charcoal particles were measured multiple times to approximate their larger contribution to sample volume. Three samples were sufficiently deflated by post-fire erosion to make the 100-measurement minimum

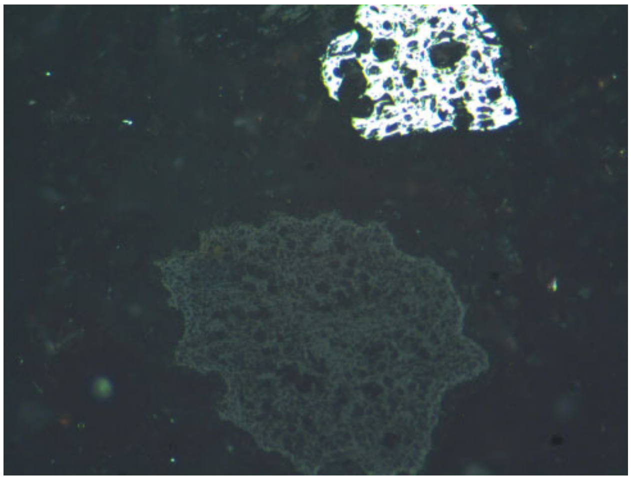

Fig. 3. Reflectance photomicrograph showing both low-reflecting and high-reflecting charred particles from sample TRF 5 (Thompson Ridge Fire). Field of view is ~0.9 mm wide.

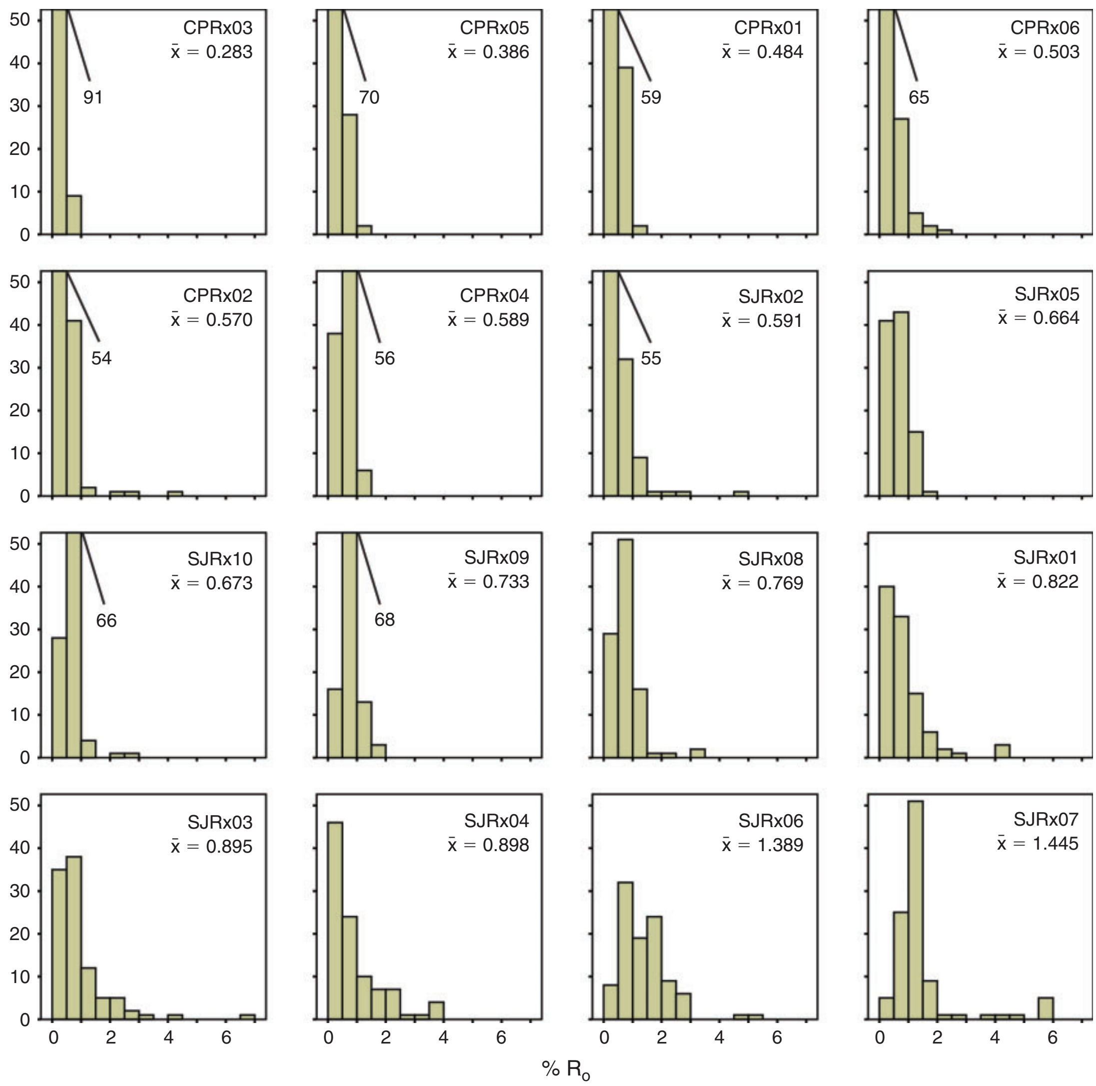

Fig. 4. Histograms of charcoal reflectance by sample for all surface fire samples organised in ascending order by mean %Ro (percentage reflectance under oil) starting from the top left. Note that all CPRx (Chaparral prescribed burn) samples and five of the SJRx (San Juan prescribed burn) samples have mean %Ro less than 0.77 and very few measurements above 1%Ro. These are all samples from natural, non-masticated fuels. The remaining five SJRx samples have increasing numbers of measurements above 1%Ro and two samples have the majority of their measurements above 1%Ro. These are all samples collected from masticated fuels.

impossible to achieve within a reasonable time frame, so only 50 points were measured.

Reflectance measurements were handled in two ways. First, individual measurements were treated as independent observations for the particular fire behaviour type ($n = 1600$ for surface fires; $n = 1550$ for crown fires). Second, reflectance measurements were treated as related observations for fire behaviour at a particular point location within a fire. In other words, we treated the reflectance measurements from a particular sample as an assemblage of related observations that could be considered in aggregate for each sample. The sample assemblages for a particular fire behaviour or fuel type were described using different metrics, including sample mean %Ro, sample median %Ro, and the percentage of assemblage measurements < 1%Ro.

Statistical tests of difference were used to evaluate whether or not charcoal measurements and assemblages formed by crown fires could be distinguished from those produced by surface fires using their mean or median random reflectance measurements, and the percentage of measurements < 1%Ro. Because the distributions of all reflectance measurements are right-skewed (data not shown, but see Figs 4, 5), and the number of samples for each category were small, we employed the non-parametric Mann–Whitney U test to compare the assemblages. The Mann–Whitney U test is a non-parametric two-sample test of difference, similar to the *t*-test, which is appropriate for small samples and those that are not normally distributed. Rather than comparing the means of two groups of measurements, all measurements of both groups are ranked and the test compares

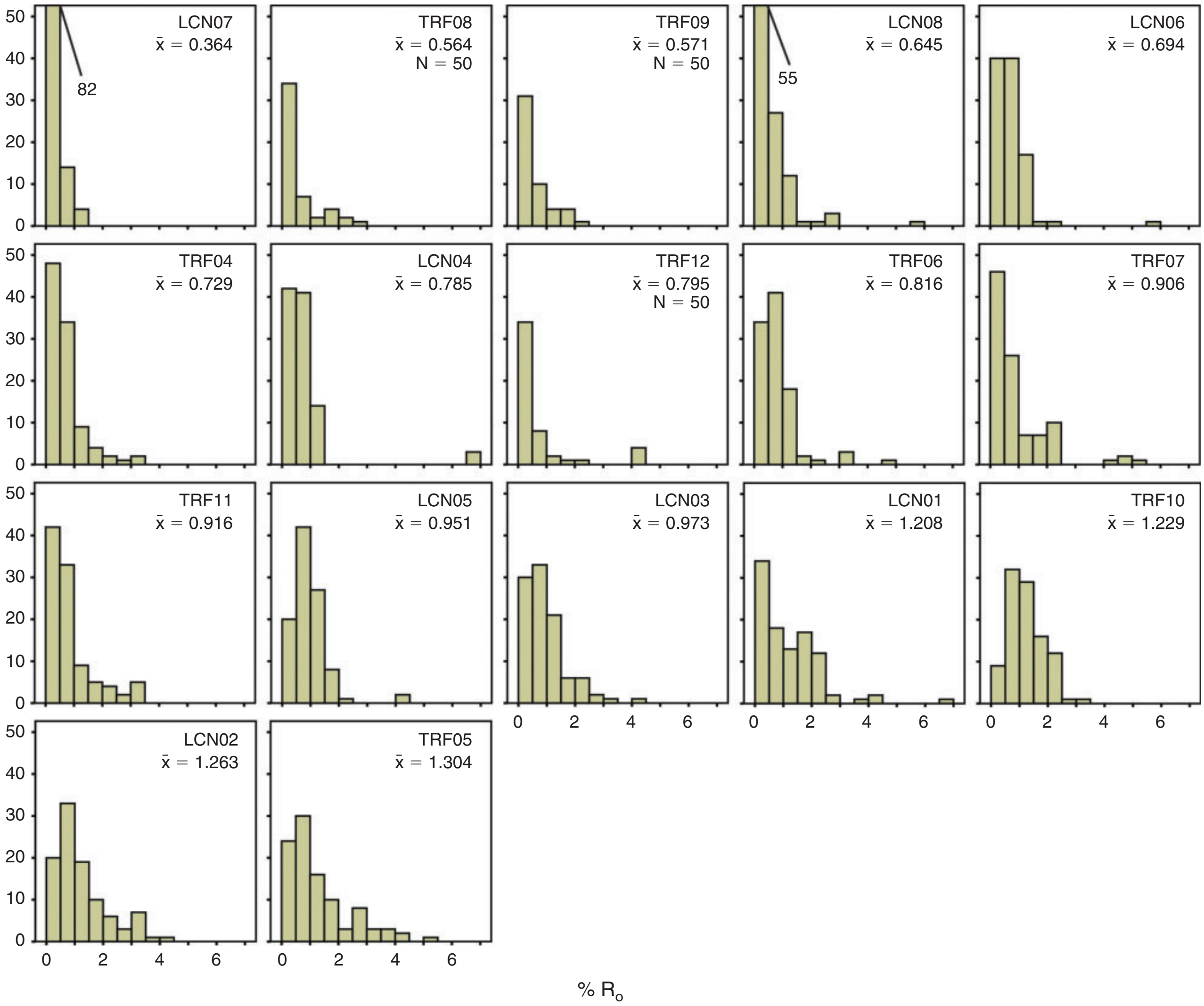

Fig. 5. Histograms of charcoal reflectance by sample for all crown fire samples organised in ascending order by mean %Ro (percentage reflectance under oil) starting from the top left. Note that six crown fire samples have mean %Ro below 0.77 and very few measurements above 1%Ro, similarly to the surface fire samples in natural fuels (Fig. 4). The remaining samples have higher mean %Ro and significant numbers of measurements above 1%Ro (at least 20% of measurements).

the ranks for measurements between the two groups. The U value is the smaller of the pairwise differences in rank for the two groups, and the U statistic (or *Z* statistic for large samples) and sample size determine significance of the test (Mann and Whitney 1947; Shennan 1997, pp. 65–68; Ott and Longnecker 2001, pp. 287–296). First, we compared crown vs surface fire behaviour discretely, then we separated surface fires in grass, duff and litter fuels from those in masticated fuels for comparison with crown fires.

Although 33 measured samples is a fairly large number for charcoal reflectance studies (cf. Jones *et al.* 1991; McParland *et al.* 2009*a*, 2009*b*, 2010; Ascough *et al.* 2010; Hudspith *et al.* 2014, 2017; Veal *et al.* 2016), we recognise that this sample size and the opportunistic sampling strategy may not be sufficient to capture the entire range of variability in temperature or fire severity within the burned areas or the different fuel types. However, the within-locality replication and replication across fire types provide a secure basis for comparing charcoal from crown fire and surface fire contexts and demonstrate the potential of the technique.

Results

Of the 33 samples, 100 measurements per sample were achieved for 30 samples, producing a total of 3150 measurements (Table 2). For each fire behaviour type and fuel type within surface fires, the measured particles were dominated by low-reflectance values, producing right-skewed distributions (Figs 4, 5). The mean reflectance values for all crown fire measurements is 0.883%Ro, whereas the mean reflectance values for all surface fire measurements is 0.731%Ro. By contrast, the median reflectance values for all crown fire

Table 2. Summary statistics of reflectance measurements of modern wildfire charcoal discussed in the paper
Note that values for surface fire charcoal in masticated fuels are more similar to crown fire charcoal in all measures, whereas surface fire charcoal in natural fuels is generally dominated by low-reflecting particles. %Ro, percentage reflectance under oil

Sample and fire behaviour context	$\%Ro_{mean}$	$\%Ro_{median}$	Measurements < 1%Ro (%)
Surface fires with natural fuels	0.289–0.769	0.381–0.641	80.0–100.0
Surface fires with masticated fuels	0.591–1.445	0.468–1.188	30.0–87.0
Crown fires	0.364–1.303	0.292–1.138	41.0–96.0

measurements is 0.627%Ro, whereas the median reflectance values for all surface fire measurements is 0.549%Ro. Although the distributions of these measurements are superficially similar (data not shown), these differences are statistically significant ($n = 3150$; $Z = -4.396$; $P < 0.001$), with crown fire reflectance measurements tending to be higher than surface fire measurements. This is predominantly driven by the differences between crown fire measurements and surface fire measurements from samples in contexts dominated by natural fuels ($n = 2450$; $Z = -8.765$; $P < 0.001$). It is important to note, however, that there is substantial overlap in the distributions of crown fire and all surface fire reflectance measurements. Only with such large numbers of measurements is this statistical segregation possible when the measurements are treated as independent observations.

When the measurements are treated as assemblages from a particular context aggregated by sample, the difference between all surface fire samples and all crown fire samples is more ambiguous. Charcoals from crown fires and surface fires in natural fuels are easily distinguished from one another but the inclusion of surface fire charcoals from masticated fuels dilutes this distinction. Figs 4 and 5 summarise the sample-by-sample charcoal reflectance measurements from surface fire (Fig. 4) and crown fire contexts (Fig. 5). Sample median %Ro, the preferred descriptor in many recent papers (e.g. Hudspith *et al.* 2015; Belcher and Hudspith 2016), and sample mean %Ro are not significantly different at the 0.005 level between the two fire behaviour types when all fuel types are considered. Only the percentage of all measurements < 1%Ro is significantly different between all surface samples and all crown fire samples ($n = 33$; U = 80.5; $P = 0.045$). Much of this ambiguity is generated by the treatment of surface fire samples from masticated fuels and grass, duff and litter fuels (i.e. 'natural' fuels) as one population (Fig. 6*a*, *b*). When all crown fires and surface fires from natural fuels are compared (Fig. 6*c*, *d*), Mann–Whitney U tests indicate that these fire behaviour contexts produce reflectance assemblages that are significantly different in terms of sample mean %Ro ($n = 26$; U = 24; $P = 0.005$) and the percentage of measurements < 1%Ro ($n = 26$; U = 13; $P = 0.001$) but not in terms of sample median %Ro ($n = 26$; U = 49; $P = 0.138$). In other words, in natural fuels (i.e. non-masticated fuels), surface fire charcoal samples are statistically distinguishable from crown fire charcoal samples. Sample median may be less useful in segregating fire behaviour types because it is insensitive to extreme values, which appear important for distinguishing these fire contexts (Figs 4, 5). Furthermore, there appear to be thresholds in mean %Ro and percentage of measurements < 1%Ro that separate virtually all crown fire samples from all natural fuels surface fire samples. Above sample mean 0.77%Ro, all samples can be assigned to crown fire contexts. Similarly, samples with fewer than 80 measurements less than 1%Ro can be unambiguously assigned to a crown fire context. The inverse is not true, in that some crown fire samples have values in the range of surface fire samples.

As dead fuel moisture was similar across all fires, fuel moisture cannot explain the reflectance differences between the fire behaviour types in natural fuels. Rather, the best explanation is that the integrated temperature and duration of combustion in surface fuels under crown fires is higher than it is for surface fires (Belcher and Hudspith 2016). In terms of soil impacts, this generally corroborates field observations for these fires that indicate higher fire severity under crown fires than under surface fires. The high-reflecting charcoal assemblages from masticated fuels suggests that these environments also experience higher integrated temperatures and durations of combustion than surface fires in natural fuels, particularly when coarse fuel moisture is low. It is important to note, however, that our sample size for masticated fuels is fairly small and that the issue of fire severity in masticated fuels would benefit from further study (Kreye *et al.* 2014). Our results suggest that charcoal reflectance may be an important tool in that research.

Our results also suggest that charcoal reflectance may be a useful tool in post-fire assessment, providing an independent, semiquantitative measurement of fire severity (Belcher and Hudspith 2016) that can work in crown and surface fire contexts. Furthermore, our results highlight the potential of charcoal reflectance to reconstruct dynamics in fire behaviour and severity from geological contexts (e.g. Hudspith *et al.* 2015). This application may be a useful new avenue to investigate the long-term role of crown fires in dry south-western forests.

Conclusions

Charcoal particles on soil surfaces from crown and surface fire behaviour contexts are statistically distinguishable. This works best when samples are repeatedly measured and treated as charcoal assemblages than when individual measurements or particles are treated independently. Although reflectance measurements for samples are non-normally distributed, sample mean %Ro and the percentage of measurements < 1%Ro are usable metrics for distinguishing charcoal assemblages that were produced under different fire behaviour conditions. Some overlap in these distributions, particularly from low-reflecting crown fire samples, is consistent with known fire variability. This is also consistent with the importance of surface fuels for

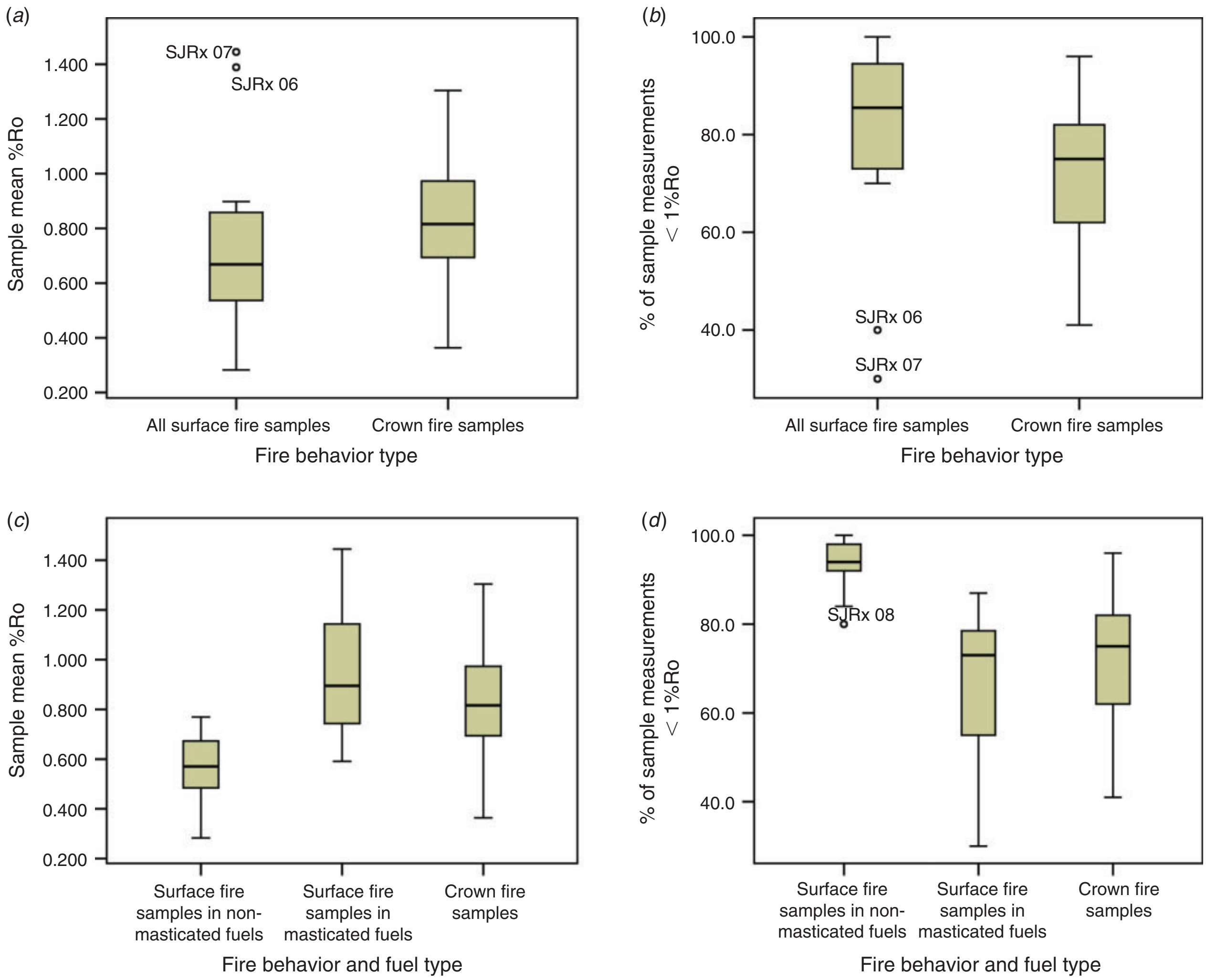

Fig. 6. Boxplots of sample mean reflectance (left column) and percentage of measurements $<$ 1%Ro (percentage reflectance under oil) (right column). The top row compares all surface fire samples with all crown fire samples (*a* and *b*). The bottom row separates surface fires in grass, duff and litter fuels (non-masticated fuels) from surface fires in masticated fuels in the comparison with crown fire samples (*c* and *d*). Note that surface fires are easiest to distinguish from crown fires when only natural (non-masticated) fuels are considered (*c* and *d*). Note also that surface fires in masticated fuels are virtually indistinguishable from crown fires, and may have slightly higher reflectance, although it is important to note that the sample size for masticated fuels is fairly small ($n = 6$).

producing charcoal on the forest floor in all fire types, so repeated sampling is necessary to correctly infer fire behaviour from charcoal reflectance.

The present study has some important implications for soil and alluvial charcoal studies of fire regime history in dry forests in the US south-west. On stable ground surfaces (Ohlson and Tryterud 2000), soil charcoal reflectance assemblages may provide a proxy for crown fire history of a given location, although these are likely a palimpsest of fires that deposited charcoal in that place. This may also be an important proxy for stratified soils in floodplain settings (Roos 2008, 2015; Roos *et al.* 2010) or in alluvial fans with stratified charred surfaces (Frechette and Meyer 2009; Bigio *et al.* 2010; Fitch and Meyer 2016). Taken together, charcoal reflectance measurements may improve our understanding of the historical role of crown fires in these ecological settings.

It is important to note, however, that the reflectance of charcoal samples from masticated surface fire contexts is virtually indistinguishable from our crown fire contexts. To the extent that charcoal reflectance is a semiquantitative proxy for fire severity (Belcher and Hudspith 2016; Hudspith *et al.* 2017), this may be troubling for land managers. Our study is limited in scope, but it suggests that fire severity (i.e. loss of organic matter and soil heating) in masticated fuels may be comparable with some crown fire contexts for which mastication is intended to protect a particular forest stand (see also Busse *et al.* 2005). Furthermore, although crown fire samples and surface fire samples in natural fuels overlap in a portion of low-reflecting measurements, samples from masticated fuels actually overlap less with other surface fire samples, suggesting greater uniformity in fire severity than in the crown fire samples. It is worth noting that the number of samples is overall quite small and that they were opportunistically collected. Although important, the results presented here may not fully represent these fire and fuel systems. Systematic sampling of post-fire surface charcoal for reflectance would improve our understanding of variability in these fire and fuel contexts as well as further develop our understanding of charcoal reflectance as a wildfire proxy.

Conflicts of interest

The authors declare no conflicts of interest.

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