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Effects of fuel morphology on ember generation characteristics at the tree scale

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Abstract. This work reports characteristics of embers generated by torching trees and seeks to identify the important physical and biological factors involved. The size of embers, number flux and propensity to ignite spot fires (i.e. number flux of 'hot' embers) are reported for several tree species under different combinations of number (one, three or five) and moisture content (11–193%). Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), western juniper (*Juniperus occidentalis*) and ponderosa pine (*Pinus ponderosa*) trees were evaluated. Embers were collected on an array of fire-resistant fabric panels and trays filled with water. Douglas-fir trees generated the highest average ember flux per kilogram of mass loss during torching, whereas grand fir trees generated the highest 'hot' ember flux per kilogram of mass loss. Western juniper produced the largest fraction of 'hot' embers, with ~30% of the embers generated being hot enough to leave char marks. In contrast, only 6% of the embers generated by ponderosa pine were hot enough to leave char marks. Results from this study can be used to help understand the propensity of different species of tree to produce embers and the portion of embers that may be hot enough to start a spot fire.

Additional keywords: fire behaviour, fuel, trees, wildland–urban interface.

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Introduction

Wildland fires can be a significant hazard to people and property in the wildland–urban interface (WUI) (Westerling 2006; Caton *et al.* 2017). An important mechanism for fire spread and ignition of structures in the WUI is via spotting through the initiation and spread of spot fires, i.e. fires that are started by embers that are lofted from the main fire front and deposited on flammable material, such as a building or biomass. Spot fires are a challenging aspect of wildfire containment because embers can be lofted past fire containment lines (Alexander 2000).

Spotting is challenging to predict in an operational context, in part because of gaps in the understanding of the three key processes involved: ember generation, transport and ignition. The latter two aspects have arguably received the most extensive research (e.g. Albini 1983; Manzello *et al.* 2006; Sardoy *et al.* 2007; Koo *et al.* 2010; Ellis 2011; Song *et al.* 2017; Caton *et al.* 2017; Tohidi and Kaye 2017), whereas less research has explored the ember generation process. Knowledge of the factors that control ember generation is a key step towards a more fully integrated understanding of the processes that govern the propensity for spotting during wildland fires.

One method to improve our understanding of the factors that influence ember generation and spotting is to collect embers during wildland fires. For example, El Houssami *et al.* (2016) and Filkov *et al.* (2016) collected embers in trays filled with water during controlled burns at the Pinelands National Reserve in New Jersey, USA. Approximately 80% of the total firebrands had a cross-sectional area of less than 2 cm^2 (Filkov *et al.* 2016). Approximately 73% of the collected embers were bark, while the rest comprised branches with diameters between 1 and 6 mm (El Houssami *et al.* 2016). It can be inferred from these studies that ember generation is species-dependent. A summary of key characteristics of embers from these and several other relevant studies is shown in Table 1.

Fire behaviour can influence ember generation characteristics, such as the number of embers deposited on a region (i.e. ember flux). Thomas *et al.* (2017) conducted an ember collection study to determine the ember flux with respect to time during a controlled burn by using cameras to record the initial time, duration and final time at which embers were deposited into pans filled with water. Fire behaviour throughout the forest, composed mainly of pitch pine (*Pinus rigida*), was monitored simultaneously in order to establish a correlation between fire behaviour and instantaneous ember flux. They found that there was nearly a direct correlation between ember flux and upwind fire intensity. In general terms, a higher upwind fire intensity

Table 1. Previous ember collection experiments MC, moisture content; NJ, New Jersey

Author	Site description	Collection method	Ember size distribution
Manzello *et al.* 2007*b*	Single 3.6-m crown height, Korean pine, 11% MC, quiescent conditions	Water trays	Cylindrical, average diameter of 5 mm and length of 34 mm
Manzello *et al.* 2007*a*	Single 2.4-m crown height, Douglas-fir, 11% MC, quiescent conditions	Water trays	Cylindrical, average diameter of 3 mm and length of 40 mm
Manzello *et al.* 2007*a*	Single 4.5-m crown height, Douglas-fir, 18% MC, quiescent conditions	Water trays	Cylindrical, average diameter of 4 mm and length of 53 mm
Foote *et al.* 2011	2007 Angora fire, white fir and Jeffrey pine with a heavy understorey	Trampoline	85% less than 0.5 cm^2
El Houssami *et al.* 2016	Controlled burn, National Pinelands Reserve, NJ, pitch pine and scrub oak understorey	Water trays, some with plastic film	80% less than 2 cm^2
Filkov *et al.* 2016	Controlled burn, National Pinelands Reserve, NJ, pitch pine and scrub oak understorey	Water trays, some with plastic film	80% between 0.5 and 2 cm^2
Thomas *et al.* 2017	Controlled burn, National Pinelands Reserve, NJ, pitch pine and scrub oak understorey	Water trays	80% between 0.075 and 0.5 cm^2
Rissel and Ridenour 2012	2011 Bastrop Complex Fire (Texas) loblolly pine with yaupon understorey	Trampolines	90% less than 0.5 cm^2
Kapcak 2015	Canadian Boreal Community FireSmart Project, no vegetation information	Water trays, fire-retardant sheets	90% of scorch marks less than 0.1 cm^2

correlated with a higher ember flux. This observation suggests that the number of torching trees and corresponding heat release influences the number of embers generated.

Identifying the characteristics (e.g. number flux and size) of ‘hot’ embers is important to better assess the risk of spot fire ignition. The average cross-sectional area of ‘hot’ embers (determined by char marks left on fire-resistant fabric) was measured during a series of prescribed burns for the Canadian Boreal Community FireSmart Project (Kapcak 2015). Approximately 90% of the char marks on the fabric were less than 0.1 cm^2 in area. The size and number of holes melted through trampolines by embers generated from wildland fires have been measured in similar efforts to quantify ‘hot’ embers (Foote *et al.* 2011; Rissel and Ridenour 2012). Foote *et al.* (2011) measured nearly 1800 holes, with 85% having an area less than 0.5 cm^2. Embers that formed these holes were likely from white fir (*Abies concolor*) and Jeffrey pine (*Pinus jeffreyi*) trees. In a related study, 90% of the holes measured were less than 0.5 cm^2 (Rissel and Ridenour 2012). These holes were likely formed by embers from a forest composed of loblolly pine (*Pinus taeda*) and yaupon (*Ilex vomitoria*). What is not fully understood from these studies is how the total number of embers that are generated (i.e. like those collected in water) compares with those that are hot enough to melt a hole in a trampoline.

The moisture content and height of trees influence the characteristics of ember generation. Manzello *et al.* (2007*a*, 2007*b*) burned Douglas-fir (*Pseudotsuga menziesii*) and Korean pine (*Pinus koraiensis*) trees in quiescent conditions, collected the embers in trays filled with water and characterised the ember size distribution. Douglas-fir trees with a 2.4-m crown height generated embers with an average diameter of 3 mm, while 4.5-m-crown-height trees generated embers with an average diameter of 4 mm. It should be noted that the heat release and tree morphology (i.e. fuel loading) change with different crown heights. The sizes of embers collected during the work just described are in the same size range as embers collected during several wildland fires (El Houssami *et al.* 2016; Filkov *et al.* 2016; Thomas *et al.* 2017). This observation suggests that some of the ember characteristics obtained from tree-scale studies may be representative of embers produced during wildland fires.

With this background and motivation, a series of tree-scale studies were conducted to elucidate tree morphological and environmental parameters that control ember generation characteristics. These studies also sought to determine the similarity of physical phenomena between different scale experiments, such as the branch-scale studies conducted previously by the authors. Hudson and Blunck (2019) observed that the diameter and species of a dowel exposed to a heated crossflow have a significant effect on the time required for an ember to be generated. This suggests that tree morphology plays an important role in ember generation at the branch scale. The specific objectives of the present work were as follows:

1. Identify the effect that tree morphology (i.e. species and fuel loading) has on ember generation characteristics,
2. Elucidate the size distribution (size, number and aspect ratio) of embers generated from different species of trees,
3. Determine the fraction of total embers generated that have sufficient energy to potentially ignite biomass.

Results from this study can be used to better understand the propensity of different tree species to produce embers. Long-term, it is expected that knowledge gained from this effort can be used when developing or improving physics-based models to better predict the transport of embers and the initiation of spot fires.

Methods

Experimental setup

Fig. 1 shows a schematic of the testing arrangement. A 3.1 × 1.2-m straw bed was constructed with the tree(s) to be torched located at one end of the bed. The average straw depth was

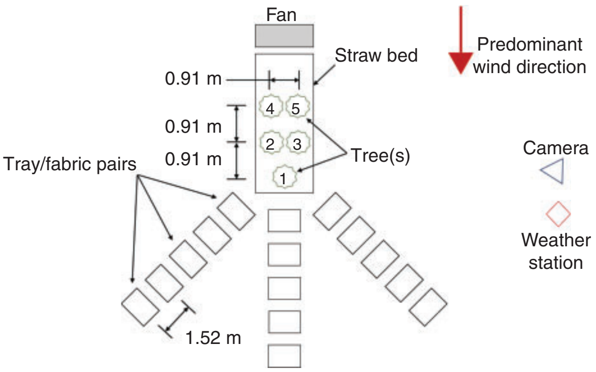

Fig. 1. Schematic of testing setup.

0.42 m, and the average straw mass was 20 kg. The bed was oriented to keep the tree(s) downwind during typical wind conditions. A visual camera was used to record videos during each test. A 1.1-m-diameter industrial fan was mounted at the upwind side of the fuel bed with a centreline height of 2.4 m. The average wind speed (recorded using a Kestrel 2000 wind meter) at the fan centreline was: 1.2 m s^{-1} at the closest row of trees, 1.0 m s^{-1} at the second row, and 0.8 m s^{-1} at the farthest tree. It was intended that the fan create a known crossflow velocity and direction, but in practice it was observed that the ambient wind dominated any crossflow generated by the fan. The average ambient wind velocity was ~0–1.15 m s^{-1}, predominately from the north (labelled on top of Fig. 1). This was based on measurements using a weather station for 15 of the 36 tests (data are shown in Table S1 available as Supplementary material). The weather station malfunctioned during the remaining tests. It is noted that variations in wind could arguably change the generation and/or the charring characteristics. However, the impact of changes in wind is expected to be relatively small (compared with the other parameters) because of the fairly low wind speeds.

Fire-resistant fabric and trays filled with water were arranged downwind of the fuel bed. Each small box on the schematic in Fig. 1 indicates a fabric and tray set, with ~1.5 m between each set and between the first row and the tree at location no. 1 (labelled in Fig. 1). Each set was oriented such that the tray was closer to tree no. 1. The trays and fabric pieces had dimensions of ~0.38 × 0.25 and 0.43 × 0.40 m respectively. The fabric was Roc-Lon cotton lining fabric from Jo-Ann Fabrics (item no. 1144484). Interested readers are referred to Hudson (2018) for images of the fabric with char marks. The advantage of using fire-resistant fabric in addition to water trays is that the fabric can be used to obtain information about the 'hot' embers that are deposited (i.e. leave char marks). Preliminary testing performed by placing a cartridge heater in contact with the fabric showed that char marks occurred for heater temperatures greater than ~575 K and contact times greater than 30 s. Hotter temperatures do not require as long to leave marks. Admittedly, at the temperature threshold just described, embers that leave marks on fabric will not necessarily lead to spotting ignition. Moreover, different fabrics may have different charring characteristics or the time that embers are hot may vary. Ultimately, these influences may alter the number of char marks detected and the characteristics reported for different fuels. Nonetheless, the number of char marks provides insights into the embers that could potentially contribute to ignition, either individually or after accumulating. Additional research is required to determine if fabric characteristics can be tailored to represent the potential for spotting ignition. Embers deposited in the water trays are immediately quenched and therefore any information about temperature and energy is lost but they provide numbers of embers per unit area and information about ember size. Embers generally consisted of needles or scales or small, indistinguishable pieces. Interested readers are again referred to Hudson (2018) for images of embers collected.

In order to vary heat release, tests were conducted with one, three or five trees (arranged as shown in Fig. 1). The species tested were Douglas-fir, grand fir (*Abies grandis*), ponderosa pine (*Pinus ponderosa*) and western juniper (*Juniperus occidentalis*). Table 2 shows morphological information for the selected species. These species were chosen owing to their widespread range in forests of the Pacific Northwest of the USA and their potential to create embers during wildland fires. Three replicates of each test were performed, which means a total of 108 trees were burned (27 of each species). Tests were conducted over a month (15 May–15 June 2018), minimising the impacts of day-to-day variations in ambient temperature and wind speed and direction. The trees were harvested and allowed to dry outside for 2–3 months, depending on when each test was conducted. Drying was necessary to ensure that the tree moisture content was low enough to allow torching to occur. Table S2 (Supplementary material) shows the initial mass, mass loss, height, moisture content and diameter at breast height (DBH) for each tree. The initial mass and mass loss were corrected for moisture content. The average tree height was 3.7 m. Trees were weighed immediately before and after each test to determine mass loss. Moisture content (dry basis) of the trees was measured immediately before testing by destructively sampling ~15 cm of two or three branches from each tree. The samples were then dried in an oven at ~105°C until the sample weights did not change. The samples consisted of small branches and accompanying needles. The average moisture contents at the time of testing were as follows: 21% (s.d. 9%) for Douglas-fir, 29% (s.d. 15%) for grand fir, 40% (s.d. 19%) for western juniper and 97% (s.d. 48%) for ponderosa pine. The ponderosa pine moisture content was generally higher than the other species despite drying the ponderosa pine trees longer. The ponderosa pine's higher moisture content reflects its high drought tolerance (USDA NRCS Plant Materials Program 2002).

At the beginning of each test, the straw bed was ignited on the upwind edge, and the fire was allowed to freely propagate. An example image of trees torching during a test with western juniper is shown Fig. 2. On average, total burning time was ~70 s from when the first tree was ignited until the trees could no longer sustain flaming combustion. The majority of embers collected were needles (or scales in the case of western juniper) and small pieces of bark. It is hypothesised that the trees and resulting torching were too small to create embers from branches. Approximately 15 700 embers and 4900 char marks were collected over all tests.

Table 2. Morphological characteristics of species tested. Information obtained from Welsh *et al.* (1987) except where noted

		Douglas-fir	Grand fir	Ponderosa pine	Western juniper
Tree	Crown shape	Open, pyramidal crown	Long, narrow crown typically with a pyramidal shape (Foiles *et al.* 1990)	Pyramidal when young but often irregular as trees mature	Generally rounded form (Fryer and Tirmenstein 2019)
	Bark	Thick, deeply furrowed, corky bark	Thin to moderately thick furrowed bark with flattened ridges (Foiles *et al.* 1990)	Thick, deeply furrowed with polygonal plates	Moderately thick, furrowed and shreddy (Fryer and Tirmenstein 2019)
Branch	Branching habit	Low-density branching with gaps	Dense branching often reaching ground level (Foiles *et al.* 1990)	Thick branches bearing long needles	Small, highly ramified branches (Dealy 1990)
	Ovulate cones	4–6-cm-long, ovoid-cylindroid	5–10-cm-long, barrel-shaped, upright on twig (Foiles *et al.* 1990)	7–15-cm-long, rounded, with a stout prickle on the umbo	6–8-mm-long, subglobose to ellipsoid berries (Dealy 1990)
Needle	Type	Flat, pointed and spirally arranged solitary needles	Flat, rounded apex, spirally arranged into two ranks (Foiles *et al.* 1990)	Long, pointed needles, mainly in clusters of three	Scalelike, awl-shaped leaves, generally arranged in whorls of three (Dealy 1990)
	Length (mm)	15–35	19–50 (Foiles *et al.* 1990)	80–100	1–2

Fig. 2. Five western juniper trees torching during a test.

Table 3. Number of embers and char marks as counted by script or manually

Tray/fabric (test number and location)	Object type	Script	Manual	Script/manual ratio
01–01	Char marks	52	48	0.92
22–02	Char marks	26	25	0.96
37–01	Char marks	145	127	0.88
30–01	Embers	208	215	1.03
10–03	Embers	11	11	1.00
06–02	Embers	47	48	1.02

Data analysis

The size and number of embers collected in the trays during testing were determined by placing the embers on a white background and taking a high-resolution picture. Pictures were also taken of each piece of fabric with char marks. Each image was then cropped and converted to grayscale. Then, each pixel was converted to either a 0 or 1 using an intensity threshold function in MathWork's MATLAB software. The number of embers or char marks was determined by counting groups of connected pixels. The area per ember or char mark was determined by counting the number of pixels per object and converting the number of pixels to an area based on the pixel resolution. The resolution for the ember images was 0.11 mm per pixel, and 0.13 mm per pixel for the fabric images.

Errors can occur when characterising the size and number of embers and char marks. One source of error is when two or more embers overlap on the fabric. The data reduction code assumed that any connected group of pixels was one char mark, even though it could be two or more overlapping marks. The number of embers or char marks was manually counted for six images (three for embers and three for char marks) in order to estimate the possible error in ember and char mark counts. Table 3 shows the number of embers by manual count and by computer script for the images. Generally, the counts determined using the computer script were within 12% of manually counted values. A second potential source of error in quantifying ember characteristics is if embers break on deposition, or if embers land on the fabric and then are blown off. Neither of these sources of error were visually observed and hence they are not considered to be a significant source of error.

Ordinary least-squares regression models were created for the two dependent variables, ember and char flux, in an effort to determine which of the test parameters influenced the ember generation characteristics. The independent parameters considered were per-test values for number of trees, average moisture content, average tree height, average tree DBH, mass loss as a percentage of initial mass, total mass loss and tree species. These values are tabulated in Table S1. The regression analysis was performed using *R* (version 3.4.2) and the *glmulti* package (Calcagno and de Mazancourt 2010).

For two tests with juniper trees, the tree(s) burned intensely enough to fully char the fabric in the row closest to tree no. 1, thus destroying the data about 'hot' embers from the fabric. All char mark data from these two tests have been excluded from the results in order to avoid potential bias.

All mass and mass loss values (Tables S1 and S2) are reported as dry mass, using the following relationship (where moisture content is represented as a fraction):

$$\text{dry mass} = \frac{\text{total mass}}{1 + \text{moisture content}} \quad (1)$$

No ember generation dependencies on wind conditions are described in this paper because there were insufficient data (owing to weather station failure) to confidently report trends. In addition, the wind speeds that were recorded were fairly low (average of 0.6 m s^{-1}) and are expected to only have had secondary effects. The authors recognise that wind conditions likely have a significant role in the generation and transport of embers. Nonetheless, it is believed that this study contributes to the community's understanding of the physics governing ember generation in wildland fires, in particular for low wind conditions.

Results and discussion

Ember and char mark characteristics

The average ember flux as a function of distance to the closest tree (i.e. location 1 in Fig. 1) is shown in Fig. 3*a*. The peak ember flux was ~1500 embers m^{-2} at 1.5 m for the western juniper and grand fir trees. At the same radial location, ponderosa pine had the lowest number flux of embers (~550 embers m^{-2}). A quadratic-like decay in ember flux with respect to distance is observed for all species of trees. This sensitivity to distance is expected because the area over which an ember can land increases as the square of radius. The percentage difference in ember flux between species stays relatively constant as the distance from the tree(s) increases. At 1.5 m from the tree, ponderosa pine generates ~1/3 of the ember flux of grand fir (548 and 1478 embers m^{-2} respectively). When the distance is increased to 7.6 m, ponderosa pine again generates ~1/3 of the ember flux of grand fir (4 and 11 embers m^{-2} respectively). Uncertainty is not shown in Fig. 3*a* because each point is the average over tests with different numbers of trees (one, three and five). However, representative standard deviations are reported. The standard deviation in ember flux for tests with five Douglas-fir trees is 54% at the closest distance and 173% at the farthest distance. The relative standard deviation in ember flux for tests with three western juniper trees is 75% at the closest distance and 173% at the farthest distance.

The average char mark flux relative to the distance from the closest tree is shown in Fig. 3*b*. The reader is reminded that 'ember' refers to tree material collected in the water trays, whereas 'char mark' refers to the marks left on the fire-resistant fabric by hot embers. The maximum char mark flux is ~375 char marks m^{-2} at 1.5 m (for western juniper). This is ~25% of the highest number flux for embers, which shows that the majority of the embers generated by the trees are not hot enough to char the fabric. The lowest number flux of char marks is produced by ponderosa pine (30 char marks m^{-2}). A quadratic-like decay in the char mark flux is also observed (similar to the quadratic-like decay for the ember flux). It is observed that the percentage difference in char mark flux between species decreases only marginally as the distance from the tree(s) increases. Ponderosa pine generates ~10% as much char mark flux as western juniper at a distance of 1.5 m (29 and 361 char marks m^{-2} respectively). Ponderosa pine generates ~5% as much char mark flux as western juniper (0.4 and 14 char marks m^{-2}) at 7.6 m from the tree(s). These observations illustrate a species dependence of the number of embers and char marks, and of the ratio of char marks to total number of embers. Similarly to Fig. 3*a*, uncertainties are not shown in Fig. 3*b*, but representative relative standard deviations were calculated. The relative standard deviation in char mark flux for tests with three Douglas-fir trees is 82% at the closest distance and 132% at the farthest. Tests with one western juniper have relative standard deviations of 42% at the closest distance and 133% at the farthest.

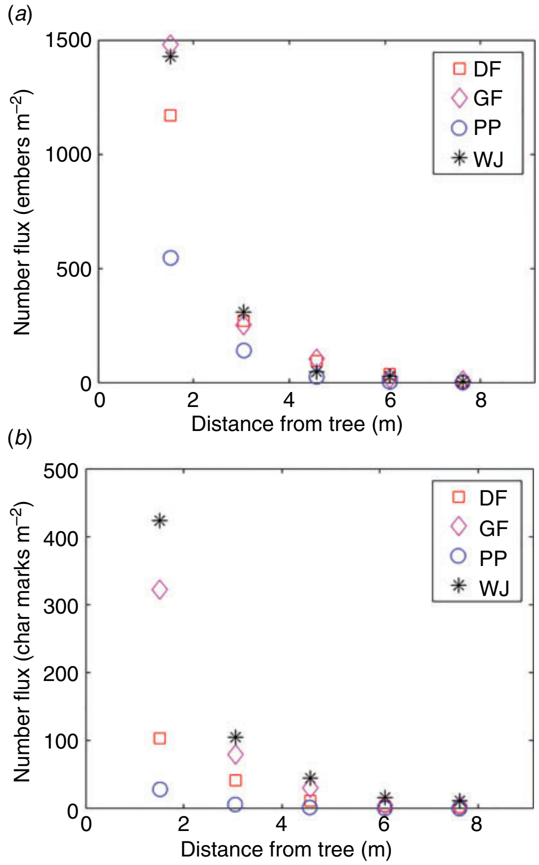

Fig. 3. Average ember flux (*a*), and char mark flux (*b*), with respect to distance from the closest tree. DF, Douglas-fir; GF, grand fir; PP, ponderosa pine; WJ, western juniper.

Fig. 4 shows a boxplot of the specific ember flux (ember flux per kilogram of mass loss) and specific char mark flux (char mark flux per kilogram of mass loss) for each test. Each 'box-and-whiskers' represents three data points (i.e. three replicates for each test case). Generally, the specific ember flux is observed to decrease as the number of trees increases. The highest median specific ember flux value when only one tree was burned was ~180 embers m^{-2} kg^{-1} (Douglas-fir). In contrast, the highest median specific ember flux value was 27 embers m^{-2} kg^{-1} when five trees were burned (ponderosa pine). This reduction in specific ember flux is likely due to embers

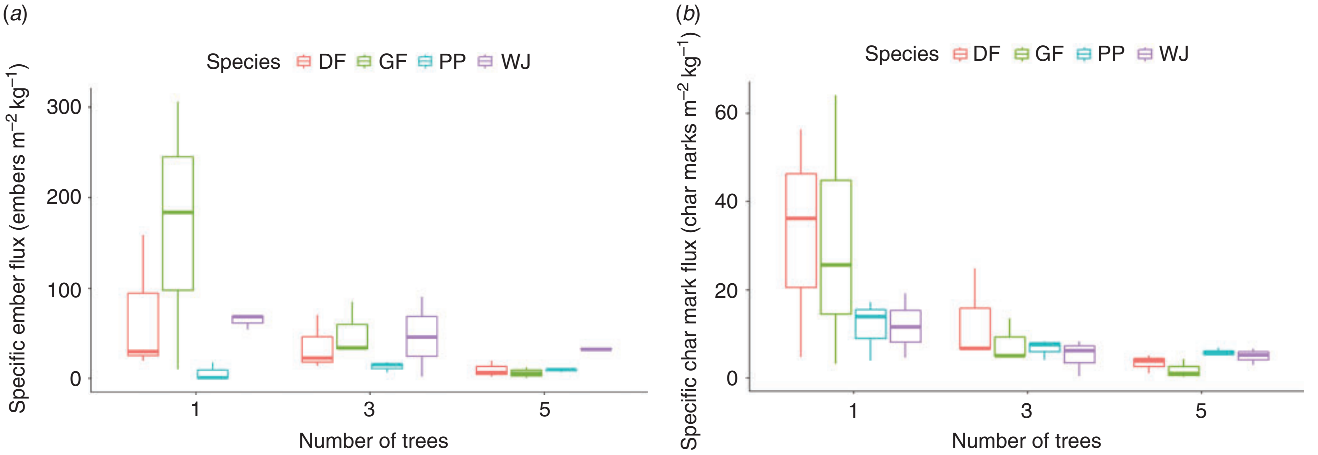

Fig. 4. Specific ember flux (*a*), and specific char mark flux (*b*), with respect to number of trees per test. DF, Douglas-fir; GF, grand fir; PP, ponderosa pine; WJ, western juniper.

generated from tree(s) upwind being blocked by adjacent trees or being fully consumed by the fire before they are able to be transported downwind. It was also observed that the difference in specific ember fluxes for different species decreases as the number of trees increases. When one tree is burned, western juniper has the lowest median specific ember flux (57 embers m^{-2} kg^{-1}), which is 30% of the highest median specific ember flux (Douglas-fir, 181 embers m^{-2} kg^{-1}). In contrast for tests with five trees, the median specific ember flux for Douglas-fir is 19 embers m^{-2} kg^{-1}, which is 73% of the median specific ember flux of 26 embers m^{-2} kg^{-1} for western juniper. This observation suggests that for large fires (assuming the same mass is lost for each species of tree), the species of trees may not have as much effect on the specific ember flux as when only a few trees are burned. More research, with more trees burned per test and different spacing of trees, are needed to determine any limits for the specific ember flux generated with respect to the number of trees.

On average, the specific char mark flux decreases as the number of trees increases (shown in Fig. 4*b*), similarly to the specific ember flux. The median grand fir char mark flux decreases from 37 to 1 char mark m^{-2} kg^{-1} for one and five trees respectively. In contrast, ponderosa pine trees display almost no change in specific char mark flux when the number of trees increases. The median ponderosa pine specific char mark flux is 0.5 char marks m^{-2} kg^{-1} for one tree and 2 char marks m^{-2} kg^{-1} for five trees.

The average specific ember flux and average specific char mark flux for each species of tree are plotted in Fig. 5. This information is useful because it can be used to help scale results to trees of different heights and fuel loading if fuel consumption rates can be estimated. Note that each data point represents the average from 27 trees. Douglas-fir trees generated the highest average specific ember flux, whereas western juniper trees produced the lowest (81 and 36 embers m^{-2} kg^{-1} respectively). Recall that western juniper generated a similar ember flux to Douglas-fir and grand fir (see Fig. 3*a*); this indicates that its lower specific ember flux is due to western juniper trees losing a greater mass than other species. Grand fir and western juniper

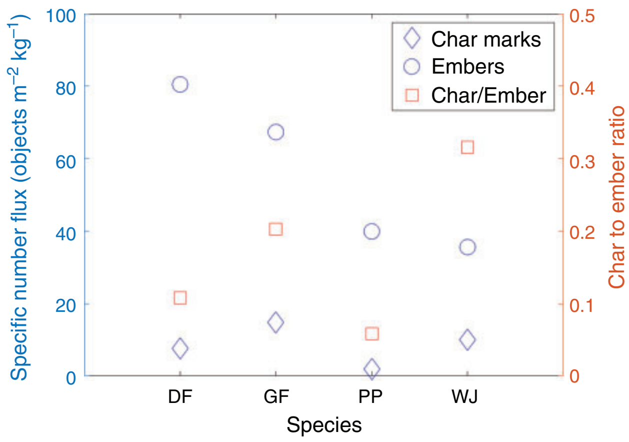

Fig. 5. Total number of embers and char marks generated per kilogram mass loss with respect to species. DF, Douglas-fir; GF, grand fir; PP, ponderosa pine; WJ, western juniper.

generated the highest specific char mark flux, with average specific char mark fluxes of 15 and 10 char marks m^{-2} kg^{-1} respectively. Ponderosa pine generated ~2 char marks m^{-2} kg^{-1}, which is the fewest of the species tested. Fig. 5 also shows the average ratio of char marks to embers for each species, which can be thought of as the fraction of 'hot' embers. Western juniper has the largest char/ember ratio (32%), indicating that on average, western juniper generated the highest fraction of 'hot' embers. Ponderosa pine generated the lowest fraction, with only 6% of the total ponderosa pine embers collected being hot enough to leave char marks. The results shown in Fig. 5 are noteworthy because they show that there is a difference in the fraction of 'hot' embers generated by the different species. In addition, it is observed that the fuel species affects the specific ember flux and specific char mark flux.

Table 4 shows the average ember and char mark areas for each species. The average and 90th percentile char mark areas are larger than the respective ember areas for all species except ponderosa pine. This is attributed to heat conducting across the fabric, which chars a region larger than the cross-section of each ember. Western juniper has the largest char mark area on average, despite having the smallest average ember area. The observation that western juniper has the smallest ember area is expected given that generally western juniper trees have the smallest needles or scales of the species tested (Table 2). The large char mark area for western juniper is attributed to the qualitative observation that only ash remained on the surface of the char marks for western juniper tests. The observation of ash suggests a larger heat release (i.e. more complete combustion) from western juniper embers than embers from the other species, and thus more energy transferred to the fabric. In contrast, charred or partially charred embers (i.e. not ash) remained on the fabric for the other species of trees. The average char mark area for ponderosa pine was ~11 mm^2, which is smaller than the average area of embers generated by ponderosa pine and ~5× smaller than the average char mark areas for the other species. This observation, along with the low char mark flux to ember flux ratio for ponderosa pine (see Fig. 5) may indicate that ponderosa pine embers (mostly needles in this study) cool more rapidly during transport than other species.

Previous work that used fire-resistant fabric to collect embers reported that 90% of char marks had an area less than 10 mm^2 (Kapcak 2015). In contrast, the 90th percentile char mark areas in the present study range from 33 to 138 mm^2, depending on species. These values are shown in Table 4. It is possible that the larger size of char marks in this study results from the relatively close proximity of the fabric to the tree(s) where the embers were generated. All pieces of fabric in this study were within 8 m of the tree(s). The embers from the prior study travelled farther (between 10.5 and 11.7 m), and thus had more time to combust before deposition. In addition, there may be physical or chemical differences in the fabric used in each study that affect the amount of energy required to leave a char mark.

Table 4. Average and 90th percentiles of ember and char mark areas for all species evaluated

Species	Average ember area (mm^2)	Ember area 90th percentile (mm^2)	Average char mark area (mm^2)	Char mark area 90th percentile (mm^2)
Douglas-fir	15	33	56	87
Grand fir	15	34	50	108
Ponderosa pine	33	87	11	33
Western juniper	10	23	64	138

Histograms of ember areas are shown in Fig. 6 to aid in comparisons of ember cross-sectional areas with previous work. The majority of embers collected, irrespective of the species of tree, were 0–10 mm^2 in area. However, the size distribution of embers differs significantly between species, as can be seen in Fig. 6*a*. The fraction of embers in each ember area 'bin' is shown in Fig. 6*b*. Western juniper embers had the narrowest distribution of areas; ~90% of embers are less than 23 mm^2 in area. The smaller size of embers from western juniper is expected and attributed to the small size of western juniper scales (Table 2 and Miller *et al.* 2005). Ponderosa pine embers have the largest variation in area; 90% of embers have an area of less than 87 mm^2. Ponderosa pine trees generated the largest embers, with an average area of 33 mm^2. Overall, the ember areas for this study are smaller than previous studies. Manzello *et al.* (2007*a*) collected embers with average areas of 120 and 212 mm^2 generated from Douglas-fir trees with 2.4- and 4.5-m crown heights respectively. The cause for the smaller ember areas in this study requires further investigation, but is likely due to differences in the experimental arrangement (e.g. method of tree ignition, collection tray locations and size of filter used to screen embers from the water).

Significance of parameters influencing generation

A regression model was created to help identify the most significant physical parameters (within the scope of variables in

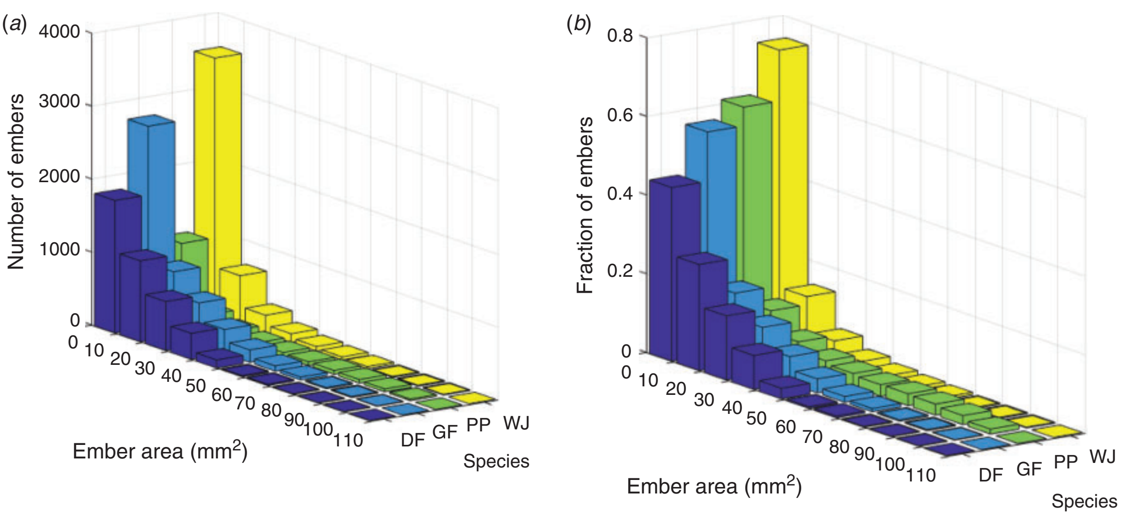

Fig. 6. Histogram of ember areas for each species tested (*a*); and histogram with bin counts normalised by species (*b*). DF, Douglas-fir; GF, grand fir; PP, ponderosa pine; WJ, western juniper.

this study) influencing ember and char mark generation. The linear regression model for ember flux (EF, units of embers m^{-2}) is:

$$EF^{1/3} = \beta_0 + \beta_1 MC + \beta_2 DBH + \beta_3 H \times MC + \beta_4 DBH \times H \quad (2)$$

where MC is the average moisture content per test and H is the average tree height per test. Note that the response variable (EF) was transformed by taking the cube root. This model was developed using the *glmulti* package in *R*, which determines the best model based on the Akaike information criteria corrected for small sample size.

The coefficient estimates (β terms) and their relative significance are shown in Table 5. The moisture content has a significant, positive effect on the ember flux for all species. It is plausible that increasing the moisture content may lead to a higher number of embers generated because of ruptures in the structure of the fuel as water evaporates and boils (McAllister and Finney 2014). Another possible explanation is that increased moisture content reduces the number of embers that are consumed by the fire in the immediate vicinity of the trees by increasing the specific heat of the embers. It is observed that there is a weak, negative effect on the ember flux with respect to the average DBH of the tree(s). Both moisture content and DBH have an interaction term with H. β_3 is significantly larger than β_4, which suggests that if moisture content and DBH are held constant, the average tree height has an inverse influence on the ember flux generated.

A regression model was created for the char mark flux per test, similar to the ember flux model, in an effort to identify key parameters that influence the generation of embers that are able to form char marks. The best linear regression model for the char mark flux (CF, units of char marks m^{-2}) was:

$$CF = \beta_0 + \beta_1 H + \beta_2 EF + \delta_1 GF + \delta_2 PP + \delta_3 WJ \quad (3)$$

where GF is the categorical variable for grand fir, PP is the categorical variable for ponderosa pine and WJ is the categorical variable for western juniper. Species of tree was treated as a categorical factor with the base case of Douglas-fir. Note that the response variable (CF) was not transformed. This model was selected based on Akaike information criteria corrected for a small sample size using the *glmulti* package in *R*.

Table 5. Estimates of coefficients and their significance for linear regression of ember flux (Eqn 2)

The significance codes are: *** <0.001 < ** <0.01 < * <0.05 < . <0.1. MC, moisture content; DBH, diameter at breast height; H, tree height

Term	Estimate	s.e.	
$\hat{\beta}_0$(intercept)	5.99411	1.19823	***
$\hat{\beta}_1$(MC)	75.39059	16.75879	***
$\hat{\beta}_2$(DBH)	−0.43399	0.11927	***
$\hat{\beta}_3$(H×MC)	−20.78155	4.49978	***
$\hat{\beta}_4$(H×DBH)	0.11907	0.02985	***
$R^2_{adjusted}$	0.3848		***

Several observations can be made about the sensitivity of char mark flux to changes in species, average tree height, and ember flux based on the β values. These values are shown in Table 6. The first observation is that the char flux is significantly affected by the species of tree (in contrast to the ember flux, which does not have a significant species dependence in the linear model). Holding all other variables constant, the model predicts no statistical difference in char mark flux between Douglas-fir and ponderosa pine. Second, we observe an inverse relationship between char mark flux and average tree height. This may be an artefact of the testing setup used. Taller trees likely loft embers farther than short trees, and these embers may have landed outside the ember collection area. A final observation is that the char mark flux is slightly dependent on the ember flux. As the ember flux increases, so does the char mark flux.

The significant effect of tree species within the char mark flux regression model suggests that inherent differences among the species tested play an important role in the ember generation process. Species characteristics at the tree, branch and needle scale, such as needle type, needle diameter and branching habit (Table 2) likely affect both the potential number of embers that can be generated and the fraction of those embers that are suitable to ignite biomass, after controlling for tree size (i.e. tree height) and tree mass (normalised results to mass loss). Moreover, changes in the heat release between the different species may influence generation characteristics. Unfortunately, the specific tree characteristics and their potential interactions with the environment (e.g. wind flow through canopies) that could influence ember generation were not directly quantified in this study. Therefore, contained within the species effect reported here are all of the potential influences of different tree, branch and needle morphological characteristics; thus, we can only speculate on the relative contribution of each tree characteristic on ember generation.

Summary and conclusions

In this work, embers and char marks were collected during a series of tests involving the torching of Douglas-fir, grand fir, ponderosa pine and western juniper trees. A straw bed was constructed with groups of trees (one, three or five) located at one end. Downwind of the testing bed was an arrangement of

Table 6. Estimates of coefficients and their significance for linear regression of char mark flux (Eqn 3)

The significance codes are: *** <0.001 < ** <0.01 < * <0.05 < . <0.1. H, tree height; EF, ember flux; GF, grand fir; PP, ponderosa pine; WJ, western juniper

Term	Estimate	s.e.	
$\hat{\beta}_0$(intercept)	101.12727	52.57124	.
$\hat{\beta}_1$(H)	−32.25917	12.93973	*
$\hat{\beta}_2$(EF)	0.18510	0.02014	***
$\hat{\delta}_1$(GF)	46.55846	13.58187	**
$\hat{\delta}_2$(PP)	0.67005	14.18668	
$\hat{\delta}_3$(WJ)	52.04473	15.22603	**
$R^2_{adjusted}$	0.8712		***

fire-resistant fabric and trays filled with water. A total of 108 trees were burned, and ~15 700 embers and 4900 char marks were collected. 'Hot' embers were identified by char marks left on fire-resistant fabric, while ember characteristics (total count and sizes) were determined from samples collected in water trays.

The specific conclusions for this work are as follows:

1. The number of embers and char marks generated per kilogram of mass loss is dependent on the species of trees. Douglas-fir trees generate the highest specific ember flux, but they do not generate the highest specific char mark flux (i.e. 'hot' embers). Grand fir generates the highest specific char mark flux at ~15 char marks m^{-2} kg^{-1}. Ponderosa pine generates the lowest specific char mark flux at 2 char marks m^{-2} kg^{-1}.
2. Only a fraction of the total embers collected were hot enough to leave char marks on the fire-resistant fabric, and this fraction varied between species. Western juniper generated the highest percentage of 'hot' embers with ~30% of the total embers being hot enough to leave char marks (for the fabric used). In contrast, only 5% of the embers generated by ponderosa pine trees left char marks.
3. The aspects of the trees that significantly affect the ember flux are not identical to the parameters that significantly affect the char mark flux. The three most significant parameters that affect ember flux are the moisture content, average tree DBH and average tree height. The char mark flux is dependent on the ember flux, average tree height and the species of the trees burned.
4. Increasing the number of trees that burn (in a group) tends to reduce the number of embers and char marks. This is attributed to neighbouring trees blocking or burning embers.

Conflicts of interest

The authors declare no conflicts of interest.

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