AN ABSTRACT OF THE THESIS OF

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Title: Multi-Scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions

Abstract approved: ____

David L. Blunck

Spot fires caused by lofted embers (i.e., firebrands) can be a significant factor in the spread of wildland fires. Embers can be especially dangerous near the wildland-urban interface (WUI) because of the potential for the fire to be spread near or on structures. Many studies have investigated the transport of lofted embers and the subsequent ignition of material on the ground, but knowledge regarding which fuel and environmental conditions control generation rates is sparse. Such information is needed to help inform ember transport models and to assess risks of ember generation for different fuel and environmental conditions. This work seeks to identify ember generation characteristics for different fuel characteristics and environmental conditions at multiple length scales. In laboratory experiments, dowels and natural samples of approximately 125 mm long were burned in a vertical wind tunnel. The species, moisture content, diameter, crossflow temperature, and crossflow velocity

were varied. A factorial study with the time to generate an ember as the dependent variable found that diameter had the largest effect on the time required, followed by species. A subset of the data from the factorial study was used to compare manufactured dowels to natural samples. It was observed that natural samples of Douglas-fir took roughly 55% longer to generate an ember than corresponding manufactured dowel samples. At a larger scale, trees 2.1-4.7 m tall were burned in outdoor, semi-controlled conditions. Embers generated were collected in trays filled with water and on fire resistant fabric. The fire resistant fabric gives an indication of ember temperature upon deposition because only "hot" embers will char the fabric. It was found that both the number of embers and char marks are significantly dependent on the fuel species. Of the species tested (Douglas-fir, grand fir, ponderosa pine, and western juniper), Douglas-fir generated the most embers per kilogram of mass loss during testing. Grand fir and western juniper generated the most char marks per kilogram of mass loss. It was observed that western juniper had the largest percentage of "hot" embers, with roughly 60% of the embers being hot enough to leave char marks.

Multi-Scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions

by

Tyler R. Hudson

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APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial, and Manufacturing Engineering

Dean of the Graduate School

Tyler R. Hudson, Author

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX FIGURES

Figure | Page

LIST OF APPENDIX TABLES

Chapter 1: Introduction

The Wildland-Urban Interface (WUI) is the area in which residential and/or commercial structures are built nearby or in wildlands. According to the U.S. Forest Service [1], the WUI in the United States has grown by 41% in the previous 20 years. With this increase comes an increase in the threat of wildland fire to people and property. One mode of wildland fire spread that can be especially difficult to protect against is spot fires. Spot fires are fires that are created when an ember (i.e., firebrand) is lofted by the fire, transported by the wind, and deposited on ignitable material, such as biomass or a house. Figure 1.1 shows a diagram of the typical spot fire process.

Spot fires are a challenge for fire-fighting personnel because they can bypass firelines (breaks in vegetation used to prevent the spread of fire) and other methods of fire containment. These lofted embers can travel large distances, sometimes on the order of kilometers [2]. For example, during the Eagle Creek Fire in Oregon during the fall of 2017, a spot fire was started across the Columbia River from the main fire. Figure 1.2 shows a map of the fire on September 10$^{\text{th}}$. The spot fire is located on the north side of the river, about 3 kilometers from the main fire.

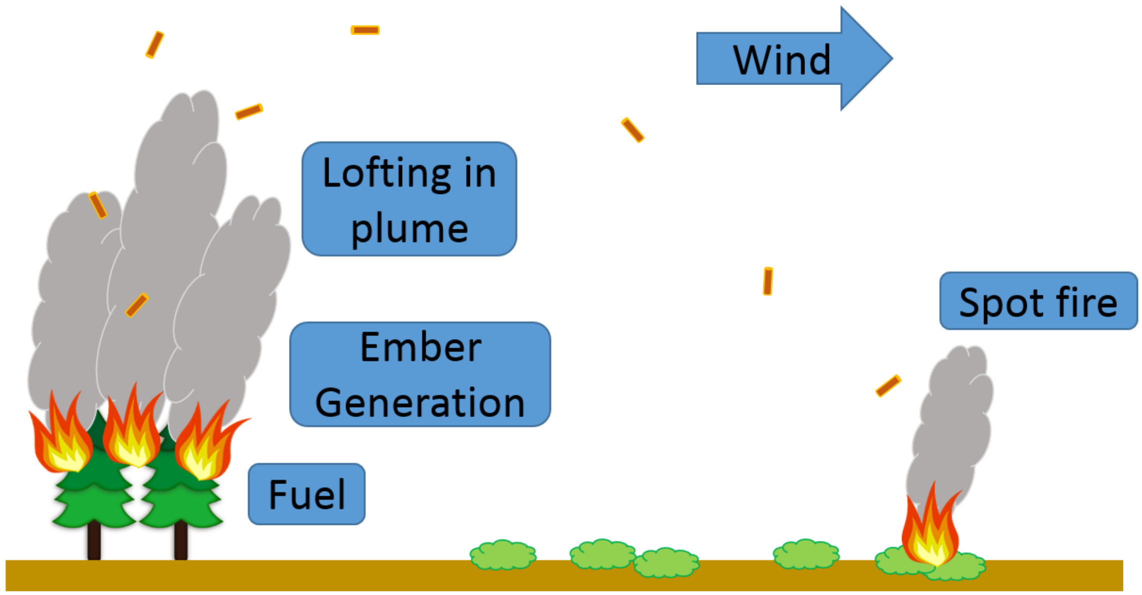

Figure 1.1: Typical spot fire process

1.1 Motivation

Another reason spot fires are challenging is that it is difficult to predict if and where one may initiate. The spot fire process is typically broken into three stages: ember generation, ember transport, and ignition. The latter two stages have received significant research (e.g., [2], [4]–[10]), while fewer studies have explored the parameters governing the ember generation process. This work focuses on the ember generation aspect of spot fires. A better understanding of ember generation is needed for several reasons. First, ember generation characteristics are necessary for source terms in ember transport models. These models allow for prediction of spot fires, and are much more useful to wildland fire managers when accurate source terms are used. Secondly, a better understanding of ember generation can be used to help assess spot

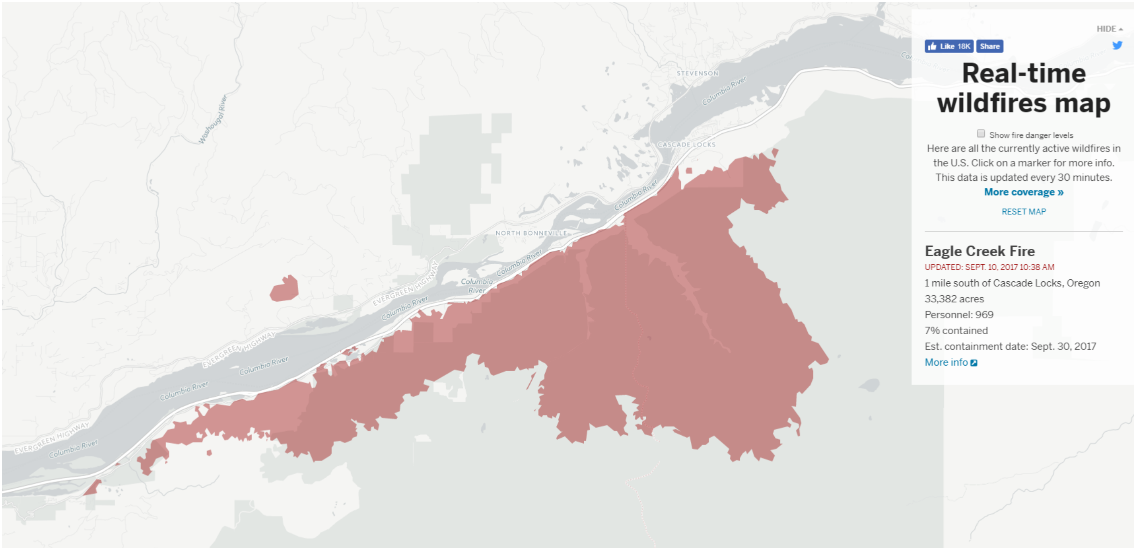

Figure 1.2: Eagle Creek Fire on September 10$^{\text{th}}$ 2017 [3]

fire risks from different fuel types.

This work is unique in the fact that it takes a multi-scale approach to the ember generation problem. Laboratory-scale, referred to as branch-scale, studies allow for precise control of variables, but may not capture all the physics that occur in full-scale wildland fires. Field studies accurately capture wildland fire physics, but variables are difficult, if not impossible, to control. For example, three controlled burns were attended during this work, but useful data was collected during only one burn. Previous research (which will be elaborated on in the literature reviews) has been conducted on either the laboratory-scale or the field-scale, but has never explored the physics shared between the different scales. This work seeks to address this gap, and will be organized accordingly.

1.2 Objective

The overall goal of this work is to expand the fire community's understanding of the parameters governing the ember generation process during wildland fires. Specifically, this work seeks to elucidate the sensitivity to fuel and environmental parameters, and the size distribution of embers with respect to fuel conditions.

The objectives of this work are as follows:

1. Determine which physical parameter has the largest effect on ember generation characteristics.
2. Identify how ember generation characteristics change when natural or processed woods are burned.
3. Determine the effect that tree morphology has on ember generation characteristics.
4. Ascertain the fraction of total embers generated that have enough energy to potentially ignite a spot fire.
5. Identify similarities or differences in the governing parameters between different scale studies.

1.3 Outline of Thesis

The main body of this work is split into two chapters: branch-scale research and tree-scale research. Each chapter is formatted for submission for peer review and has an introduction, experimental approach, results and discussion, and conclusion. Chapter 2 covers the branch-scale, factorial study conducted. Next, Chapter 3 discusses the tree-scale experiments. Concluding thoughts in Chapter 4 link results from each scale into an overall conclusion.

Chapter 2: Effects of Fuel Characteristics and Crossflow Conditions on Ember Generation Characteristics at the Branch-scale

2.1 Introduction

Wildland fires are becoming an increasing hazard to personal safety and property as a result of climate change and as the wildland-urban interface (WUI) grows [8], [11], [12]. A significant mechanism for spreading of wildland fires and a threat to structures at the WUI is spot fires. Embers (also known as firebrands) are generated at the fire and are transported by the wind away from the fire front. A spot fire can then initiate if the embers land on flammable material, such as a house or biomass [4]. Embers can travel large distances, for some conditions on the order of kilometers [2]. Lofted embers can be particularly challenging when protecting WUI areas because they can be transported past barriers which stop other mechanisms of fire spread.

The ability to predict the threat of spot fires is limited because of gaps in understanding about the physical and chemical processes that control ember generation, transport, and ignition. Thus, there is a need to better understand these processes to allow fire professionals to better assess threats associated with spot fires. Transport and ignition have received the most attention (e.g., [2], [4]–[10]), while relatively few studies have considered the processes that control generation of embers. Arguably, generation of embers is the least understood aspect of the spot fire process. This study focuses on identifying the importance of several key physical and chemical parameters that control ember generation, such as fuel species, fuel diameter, fuel moisture content, crossflow temperature, and crossflow velocity.

Numerical models of burning wooden cylinders have been used to better understand the ember generation process. Barr and Ezekoye [13] predicted breakage (i.e. ember generation) using a fractal tree model coupled with a thermal decomposition model. Breakage occurred when the strength of the cylinder degraded (due to decreased diameter because of oxidation) to less than the drag-induced stress. By coupling this model with a transport model, they found that there exists an optimal branch diameter (i.e., roughly 4 cm) for generating embers that can form spot fires. The branches need to have a small enough diameter to break during a typical fire dwell time, but large enough to not be consumed during transport. The critical diameter is significantly larger than the diameter of most samples collected during experimental studies (described later). The discrepancy between the critical diameter and those measured was attributed to differences in physical properties of manufactured dowels and natural samples; natural samples tend to have more defects, have a nonuniform shape, and are coated in bark [13].

The diameter and density of the fuel are parameters that can influence ember generation. For example, Caton [14] found a linear relationship between dowel density and flexural strength after exposure to various heating conditions. This correlation varies between species which suggests that fuel species may influence ember generation physics because of different strength characteristics (in addition to having different densities). Based on this analysis, it was reported that dowels with a diameter of 6.35 mm or less would break when exposed to typical wildland fire conditions.

Laboratory and field studies have reported the size distributions of embers for several different tree sizes, moisture contents, and species. This information provides insights into the ember generation process. Several field studies reported that embers collected during prescribed and wildland fires generally had a projected cross sectional area less than 2 cm^2 [15]–[19]. Manzello et al. [20], [21] collected embers generated from burning single Douglas-fir and Korean pine trees. Trees with a larger crown height produced larger embers (4 mm average diameter) than trees with a smaller crown height (3 mm average diameter) for similar wind speeds and moisture contents. The difference in average ember size for the different tree heights shows that tree height influences ember generation. It is worth noting that the heat release and tree morphology varied between tests as the tree height (i.e., quantity of fuel) was changed. This is important because the larger average ember size may be influenced by heat release and/or tree morphology (i.e., crown height, fuel loading, and size of branches). It was noted that trees with a moisture content greater than 70% did not sustain burning. This observation suggests that, at least at the extremes, moisture content may be an important parameter controlling ember generation.

In summary, studies like those just described have shown that that species, moisture content, crossflow velocity, diameter (i.e., related to aspect ratio), and crossflow temperature all affect the propensity of a tree to generate embers. However, the significance of these parameters relative to each other in influencing ember generation is not well understood. Knowledge about the controlling parameters can be used to help identify the propensity for ember generation from different forests and environmental conditions, and ultimately be used to inform ember generation models. With these motivations in mind, a 2^5 factorial design study was conducted to complete the following objectives:

1. Determine how the sample diameter, species, moisture content, crossflow velocity, and crossflow temperature affect the time required for embers to generate.
2. Ascertain the relative importance of the parameters just described on the time required for ember generation.
3. Identify how ember generation characteristics change when natural or processed woods are burned.

It is expected that as a result of this research, the relative importance of several parameters influencing ember generation will be known. It is hoped that this work will help identify the connection between laboratory-scale and field-scale physics, and whether burning manufactured dowels is representative of natural physics.

2.2 Experimental Approach

A vertical wind tunnel was used to evaluate the time required for ember generation for different species of trees, fuel characteristics, and environmental conditions. The wind tunnel consisted of a 150 x 250 mm duct with two propane torches (only one was operated for some conditions) and two industrial fans. This arrangement allowed the temperature and crossflow velocity to be systematically varied. A model of the wind tunnel is shown in Figure 2.1. The wood samples were placed 250 mm downstream of the torches and 950 mm downstream of the fans. One or two branches or dowel samples, oriented in the x-direction, were placed in the high temperature crossflow. Two expanded metal grates were placed between the torches and the samples to create a more uniform temperature and velocity distribution near the sample. A visual camera was used to record a video of each sample placed in the crossflow.

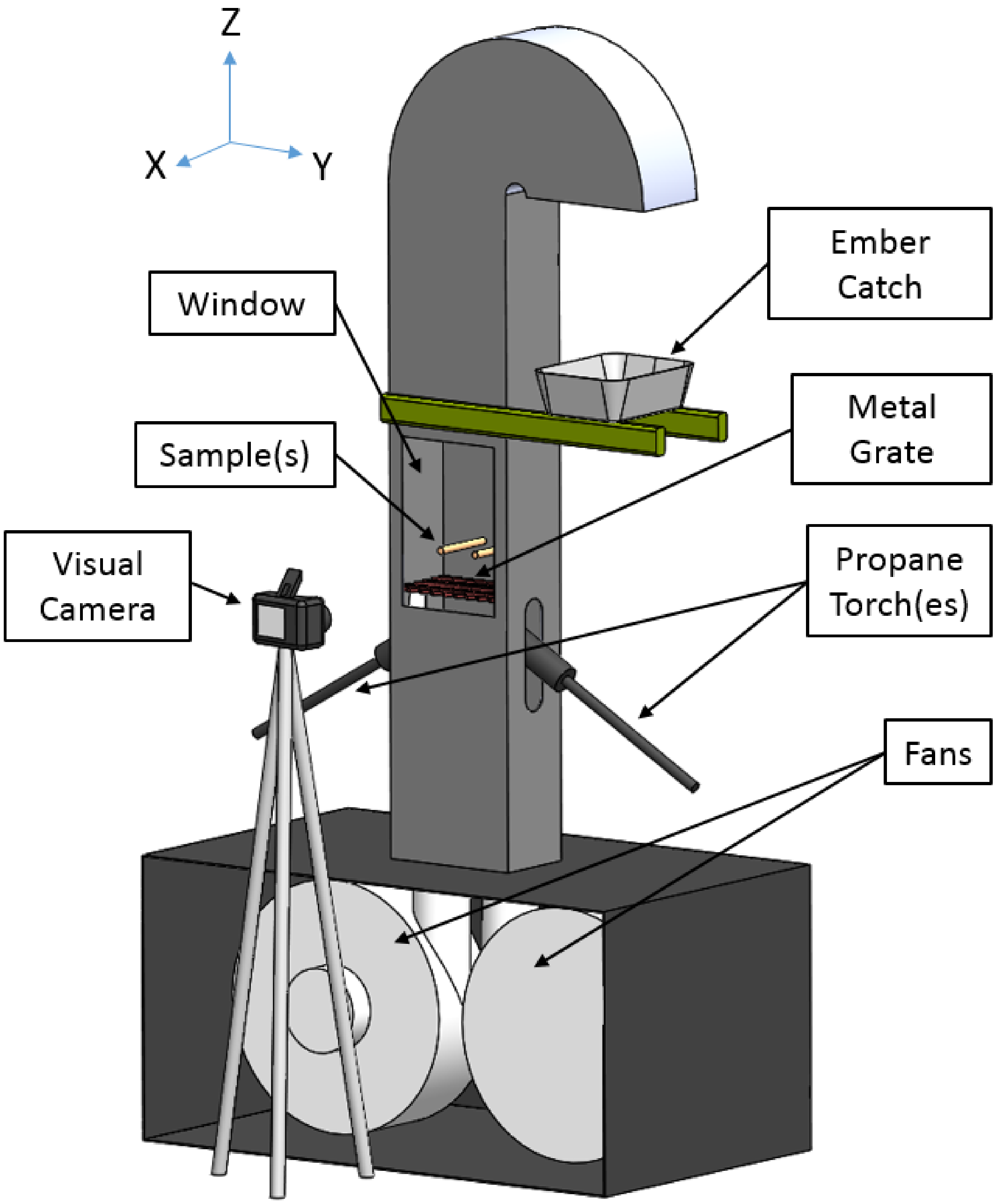

Figure 2.1: Model of the vertical wind tunnel used to evaluate ember generation characteristics

Figure 2.2 shows the average temperature distribution that each sample experienced. This was measured by traversing a type K thermocouple across the depth of the wind tunnel, in the locations where the dowels were inserted. Both high (peak = 1200 K) and low (peak = 1000 K) temperature conditions were evaluated. The temperature ranges were selected to be representative of those that a tree might experience during a typical wildland fire [22], [23]. The temperatures were controlled by metering the propane flow rate using a rotameter. Lower temperatures were observed near the walls because of cooling and the distribution of heat release from the burners. The heat release rate was between 37 and 50 kW (low and high temperature cases, respectively). By assuming simple, 1-D convective heat transfer, the heating rate of the samples can be estimated to be between 128 - 216 W for 6 mm diameter samples and between 81 - 126 W for 2 mm diameter samples. The range of heat transfer is due to the range of conditions evaluated. The grates placed downstream of the propane torches glow during testing, so radiative heat transfer from the grates to the samples was analyzed. The heat transfer rate was calculated to be approximately 8 and 3 W for the 6 and 2 mm diameter samples, respectively. This is negligible compared to the convective heat transfer.

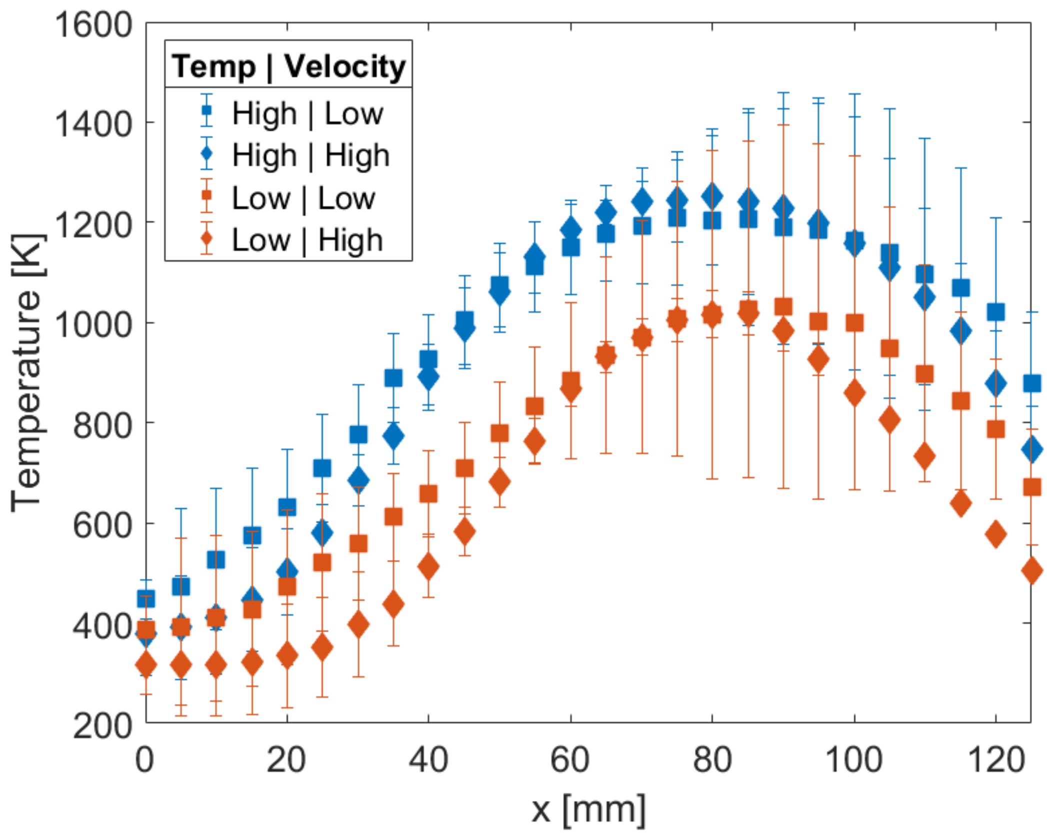

Figure 2.2: Temperature profile from base of sample (x=0) to tip of sample (x=125mm).

Figure 2.3 shows the average velocity distribution along the x-axis in the location where each sample was placed. The magnitudes of the two crossflow velocities are similar to what a branch might experience during a wildland fire [24], [25]. The uncertainty reported in Figures 2.2 and 2.3 are precision uncertainty (at least 4 replicates) with 95% confidence. The relatively high uncertainty in the temperature measurements at some locations resulted from limitations in how the fuel flow rate was metered and sensitivities in the distribution of the heat release to slight changes in the wind tunnel arrangement (e.g., warping of the wind tunnel walls).

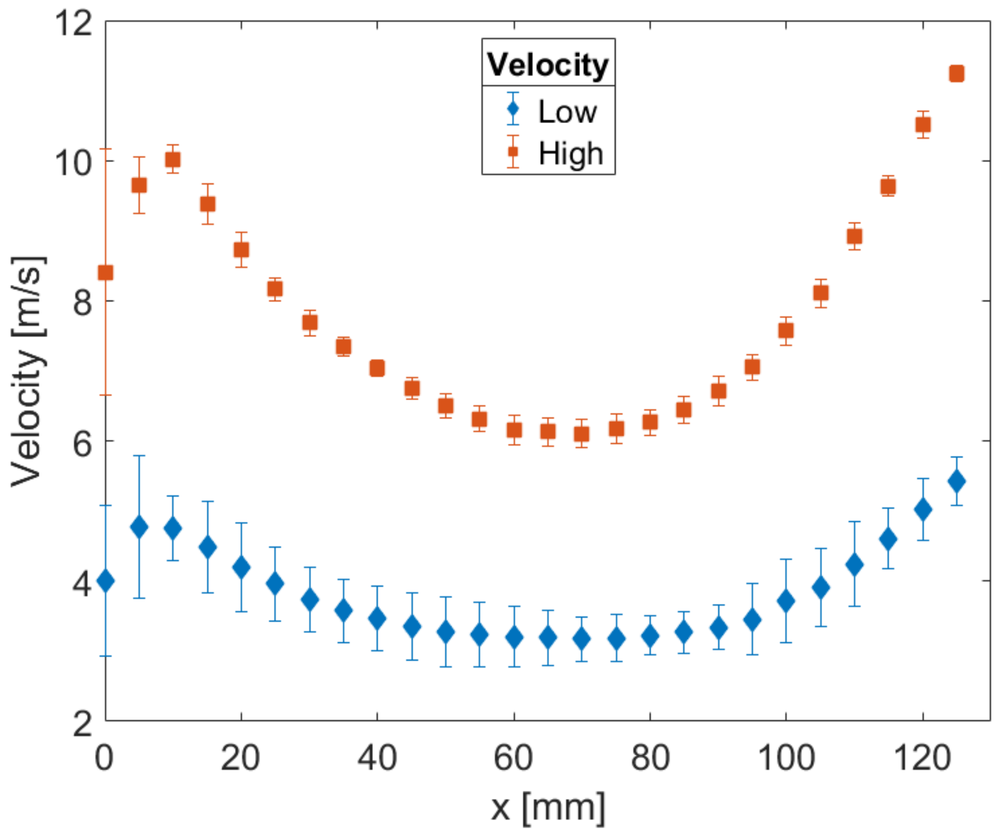

Figure 2.3: Velocity profile from base of sample (x=0) to tip of sample (x=125mm).

The physical characteristics of the samples that were varied during the experiments include: diameter (2 and 6 mm), species (Douglas-fir, western juniper, ponderosa pine, and white oak), moisture content (0.5% and 15%), and condition (dowel and natural). The objective in varying the sample conditions was to elucidate the aspects that control ember generation of branches. The nominal sample diameters were selected based on embers collected in previous studies [20], [26]. All samples were 125 mm in length, resulting in aspect ratios equal to 62.5 and 20.8 for the 2 and 6 mm diameter samples, respectively. The species were chosen for their abundance in the western United States and their contrast in tree morphology and density. The samples were dried using an oven at approximately 70 °C and weighed at periodic intervals until the mass no longer changed. By measuring the relative humidity of the room, the equilibrium moisture content of the dry dowels was determined to be roughly 0.5% [27]. The 15% moisture content samples were created by placing dried samples in a humid environment until the desired moisture content was achieved. Dowels and natural samples were investigated because they offer unique characteristics. Dowels are useful because the geometry is consistent between samples, but only partially represent physical characteristics because they have no bark and are made of heartwood. Natural samples may have inconsistent geometries, but are representative of fuels in a wildland fire. The natural samples evaluated were Douglas-fir and had average diameters of 2.05 $\pm$ 0.11 mm and 5.61 $\pm$ 0.14 mm. The average diameters of the manufactured Douglas-fir dowels had average diameters of 2.13 $\pm$ 0.06 mm and 6.14 $\pm$ 0.07 mm. Figure 2.4 shows an example of the samples used. The light-colored samples are manufactured dowels, while the darker samples are natural samples with intact bark.

Figure 2.4: Douglas-fir samples. From left to right: 6 mm diameter dowel, 6 mm diameter natural sample, 2 mm diameter dowel, 2 mm diamter natural sample

The fuel and environmental conditions evaluated were intended to be representative of wildland fires. However, the range was not comprehensive of all conditions possible in fires because of the finite scope of the project. Nonetheless, the results from this work are expected to be applicable to more extreme conditions and provide insights in ember generation for low intensity burns.

Identification of the sensitivity of ember generation characteristics to fuel and environmental conditions were made through visual observations of the time when the embers were generated and by using a design of experiments (DOE) factorial approach. The data were processed using an ANOVA in R. Each testing condition had at least three replicates. A video of each sample being burned was collected and converted into a series of images to allow for comparison between different conditions at similar times. An example ember generation from a 6 mm, oven-dried, Douglas-fir dowel is shown in Figure 2.5. The sample starts burning roughly 4 seconds after being inserted into the flow. Steady combustion is observed near the center of the sample. At 24.5 seconds, the sample deflects in the direction of the crossflow before failing and yielding an ember. The time to ember generation for each sample was defined to be the time between sample insertion and when a majority of the sample was lofted. If several small embers were generated, the generation time was defined to be the average of those generation times.

(a) (b) (c)

Figure 2.5: Sequential images of an ember generation event. The first image was taken roughly 25 seconds after the sample was exposed to the heated crossflow. The time between each image is approximately 66 milliseconds.

2.3 Results and Discussion

2.3.1 Dowel Factorial Study

The goal of a factorial study is to determine the relative importance of the independent variables on the response variable. In this study, the response is the time to generation. Figure 2.6 shows the mean square (sum of squares divided by degrees of freedom) of each statistically significant single-term effect ($P \leq 0.05$). A logarithmic scale was used to allow all of the data to be visualized. The diameter of the dowels had the greatest sensitivity on the time to formation of embers. The mean square was nearly 2 orders of magnitude greater than any other parameter. On average, 2 mm diameter samples generated embers roughly 5x faster than 6 mm, with average ember generation times of 7.1 and 35.2 seconds, respectively (average generation time for all test cases are shown in Table A.1). These times to generation are similar to those that might be found in a wildland fire. In a separate work (discussed in Chapter 3), 2.1-4.7 m tall trees were torched. On average, the trees torched for roughly 70 seconds. This suggests that the conditions the dowels experienced may be representative of conditions experienced during a wildland fire. The greater sensitivity of ember generation time to diameter is attributed to the smaller diameter dowels having a larger surface area to volume ratio. As a result, the relative mass loss rate due to oxidation is higher for the 2 mm cases, and the critical cross sectional area at which fracturing occurs is reached sooner.

The fuel species was the second most significant parameter influencing ember generation time. Of the four species evaluated, Douglas-fir and white oak had the largest difference in the average time to generation. Douglas-fir samples generated embers in roughly 64% of the time that white oak samples required (16.5 and 25.7 seconds, respectively). Crossflow temperature and velocity and fuel moisture content have little effect on the time to ember generation. The insignificance of temperature on time required for ember generation is attributed to both high and low temperature cases being above the pyrolysis and oxidation temperatures for the samples. Changes in the consumption of the fuel for the two temperatures (i.e., 1000 and 1200 K) had a secondary effect on generation time compared to other parameters. Crossflow velocity and moisture content both had weak effects on the time it takes to generate an ember. The observed sensitivities indicate that the fuel size has a greater influence on time to generation than environmental characteristics. More broadly, these results suggest that tree morphology, which controls the characteristic size of branches, may have the largest effect on the time to ember generation.

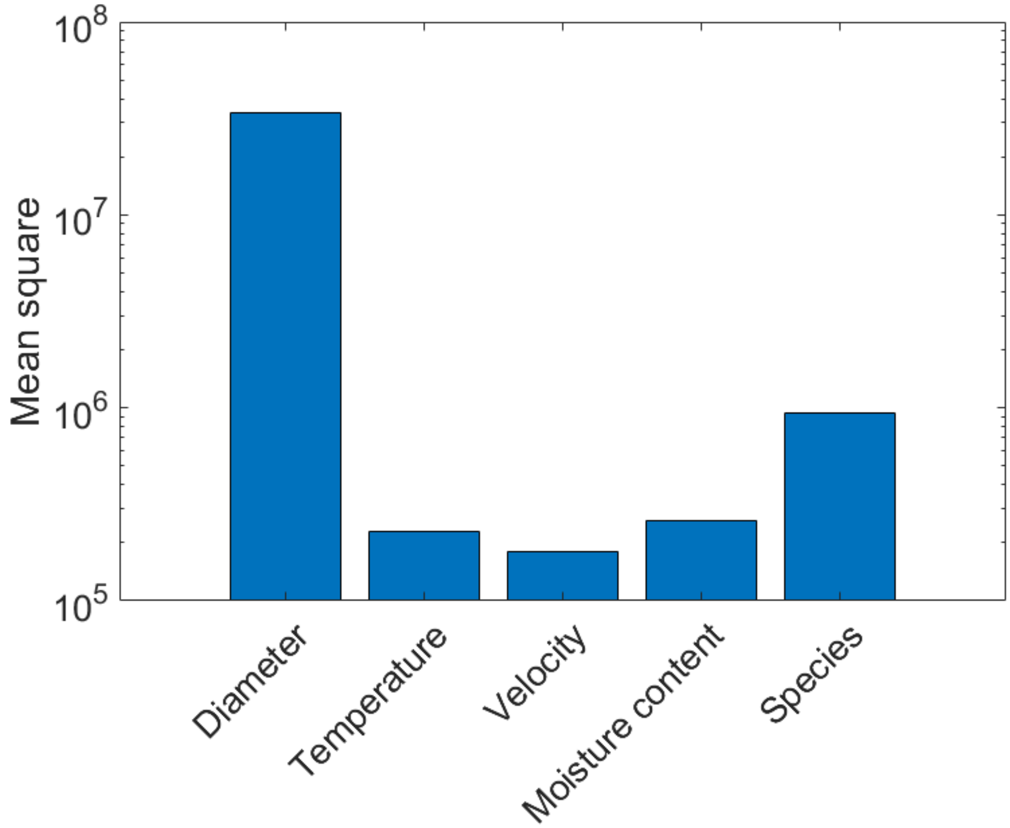

Figure 2.6: Mean square for main effects controlling ember generation

Figure 2.7 shows the mean square of each statistically significant interaction effect on time to ember generation. The diameter and species interaction had the largest influence on ember generation time, while the interaction between diameter and crossflow temperature had the weakest influence. The interaction between diameter and species can be thought of as the fuel morphology because the branch diameter distribution of a tree is dependent on its species. The observation that the interaction between diameter and species in the most important interaction term suggests that fuel morphology is critical to predicting the time required for ember generation.

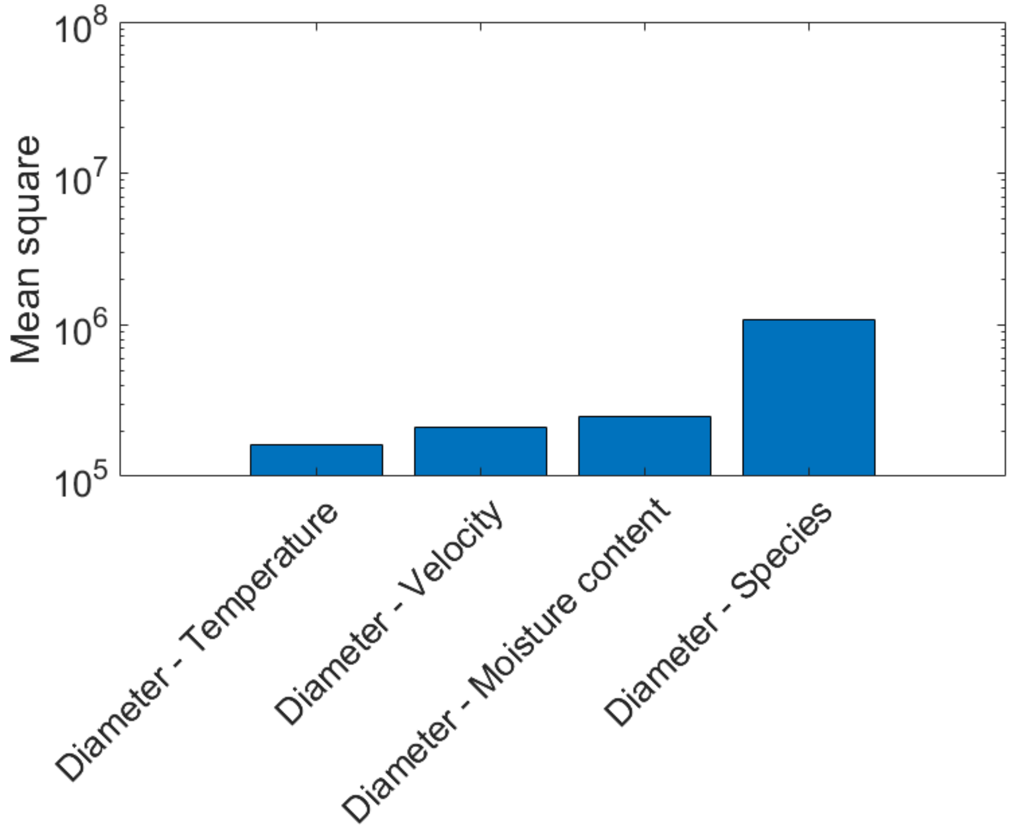

Figure 2.7: Mean square for couple interaction effects controlling ember generation

The most significant two-way interactions between key parameters were evaluated and plotted in order to better understand the coupling effects shown in Figure 2.7. Figure 2.8 shows the average time to generation for the species tested, along with the measured density of each species. Relatively little change is observed in time to generation between species for the 2 mm diameter samples, but a relatively large difference is observed for the 6 mm samples. The density of the fuels tended to be proportional to the time required for ember generation. Specifically, fuels with a higher density (e.g., white oak) tended to take longer to generate an ember.

The coupled interactions between characteristic diameter and crossflow and moisture content are shown in Figure 2.9. The time to generation for the 6 mm diameter sample decreased at a lower moisture content. This is likely due to higher moisture content increasing the heat capacity of the sample, which increases the time required to reach pyrolysis and oxidation temperature [28]. Note that there is almost no change in generation time with a change in moisture content for the 2 mm samples. Previous research suggests that the moisture content of fine fuel (i.e., 2 mm diameter) is an important parameter for the spread of wildland fires [29]. The results from this study indicate that a minimum diameter exists below which moisture content does not influence time to ember generation for fine fuel, at least for the relatively small changes in moisture content used in this study. For the crossflow interactions, the average generation time was shorter for a high crossflow, 6 mm diameter sample than for the respective low crossflow case. This occurs because the drag-induced stress increases proportionally to the square of the crossflow velocity. A higher stress means the sample requires less time to be weakened (by pyrolysis and oxidation) before breakage. Similar to previous trends, there was almost no change in generation time between high and low crossflow velocities for the 2 mm diameter samples.

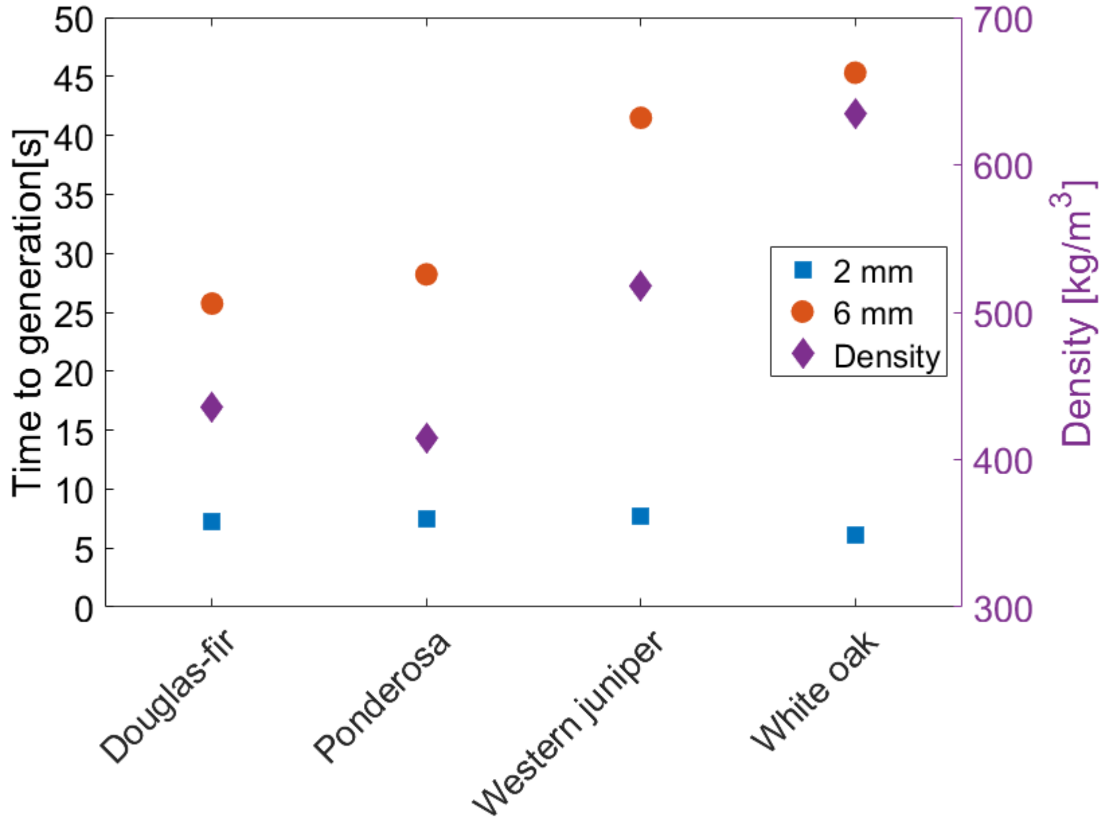

Figure 2.8: Average time to ember generation for all species tested

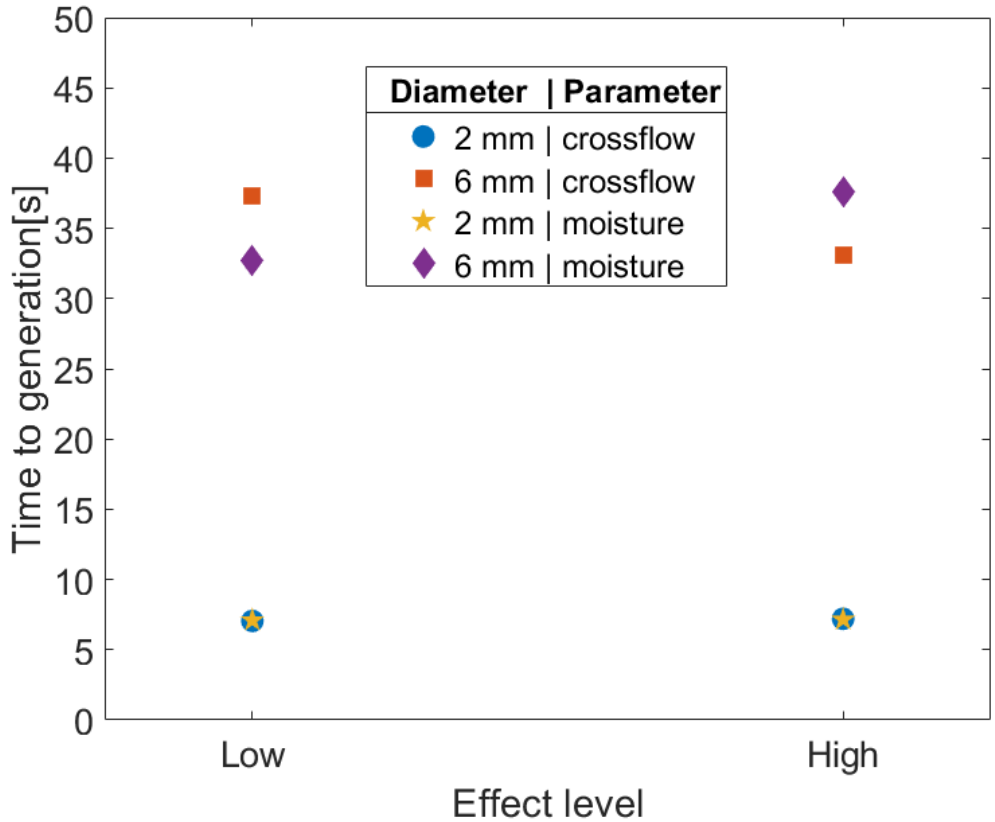

Figure 2.9: Interaction between moisture content (low: 0.5%, high: 15%), crossflow velocity, and sample diameter

The observation that 2 mm diameter samples were unaffected by changes in species, crossflow velocity, moisture content, and crossflow temperature (not shown) suggests that as dowel diameter decreases there is a critical diameter (and resulting aspect ratio) where ember generation time becomes independent of other parameters tested (within the range evaluated in this study). This is attributed to the volume of the samples being small enough that changes in the pyrolysis and oxidation rates (due to changes in density, crossflow velocity, moisture content, and heat intensity) have relatively little effect on the time required for the fuel to be consumed and facilitate breaking.

2.3.2 Evaluation of Natural Samples

A second factorial analysis was conducted to discern the effect that fuel condition (natural or dowel) has on the time to generation. The parameters varied were diameter, moisture content, crossflow temperature, crossflow velocity, and fuel condition. Douglas-fir samples were evaluated for this study. The mean square for each statistically significant single-term parameter is reported in Figure 2.10. The diameter of the sample had the greatest effect on time to generation. The second and third greatest sensitivities were the fuel condition (dowel or natural sample) and the crossflow velocity, respectively. The sensitivity to fuel condition indicates that the physical differences between dowels and natural samples do significantly affect time to ember generation. The mean squares of the diameter and crossflow velocity effects have relative magnitudes similar to those of the main factorial study (shown in Figure 2.6). Crossflow temperature had a small effect on the time required to generate an ember, similar to the results of the main factorial study. The moisture content was not a significant factor.

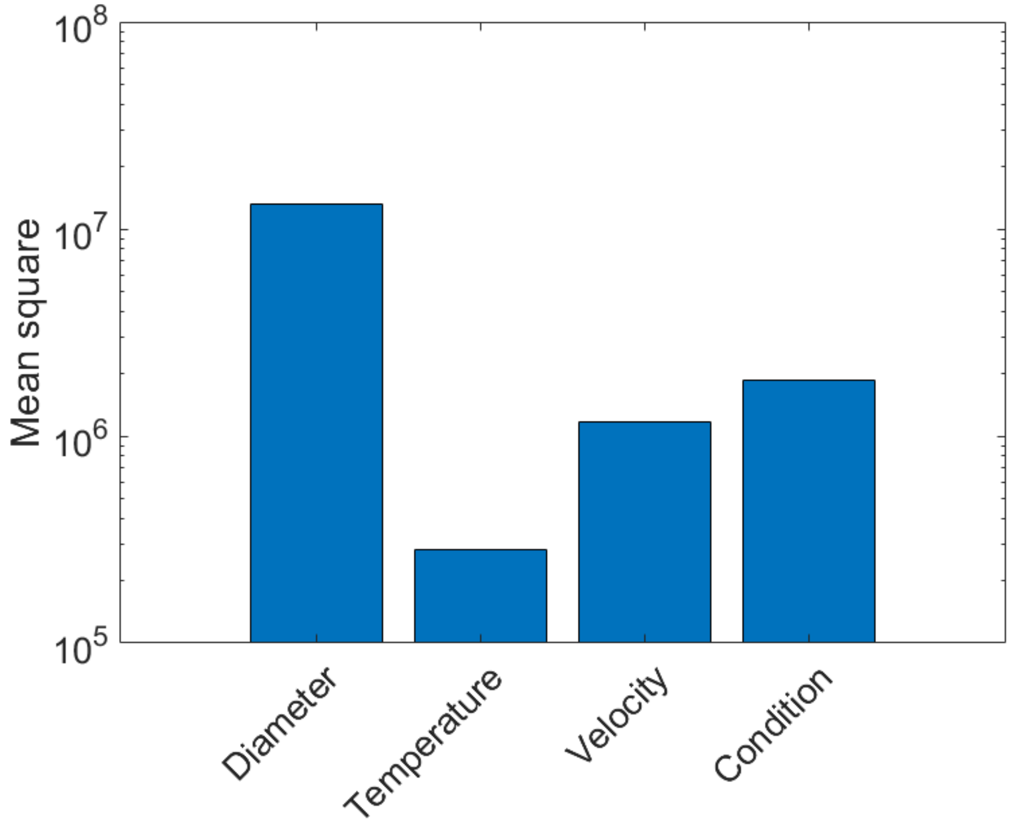

Figure 2.10: Mean square for main effects controlling ember generation when natural samples were evaluated. Fuel condition refers to natural or dowel samples.

The three greatest interaction terms for the evaluation of natural samples were diameter coupled with crossflow velocity, diameter coupled with fuel condition, and crossflow velocity coupled with fuel condition. The diameter and crossflow velocity coupling was evaluated in Figure 2.9, and is not repeated here. Figure 2.11 shows the interaction between fuel condition and diameter. The natural samples take longer to generate an ember for both 2 and 6 mm diameter samples (43% and 60% increase for 2 and 6 mm samples, respectively). Natural samples tend to have more defects and less uniformity which should decrease the time to generation. However, a significant portion of the natural samples had large deflections (see Figure 2.12) during testing, which decreased the crossflow-induced drag. Thus, the time required to generate an ember was significantly increased for these tests. Branch wood (i.e., natural samples) tends to have a lower modulus of elasticity than stem wood (i.e., manufactured dowels) [30], which may explain why many natural samples deflected significantly before breaking, and thus made the average time required for natural samples to generate an ember longer than the time required for manufactured dowels.

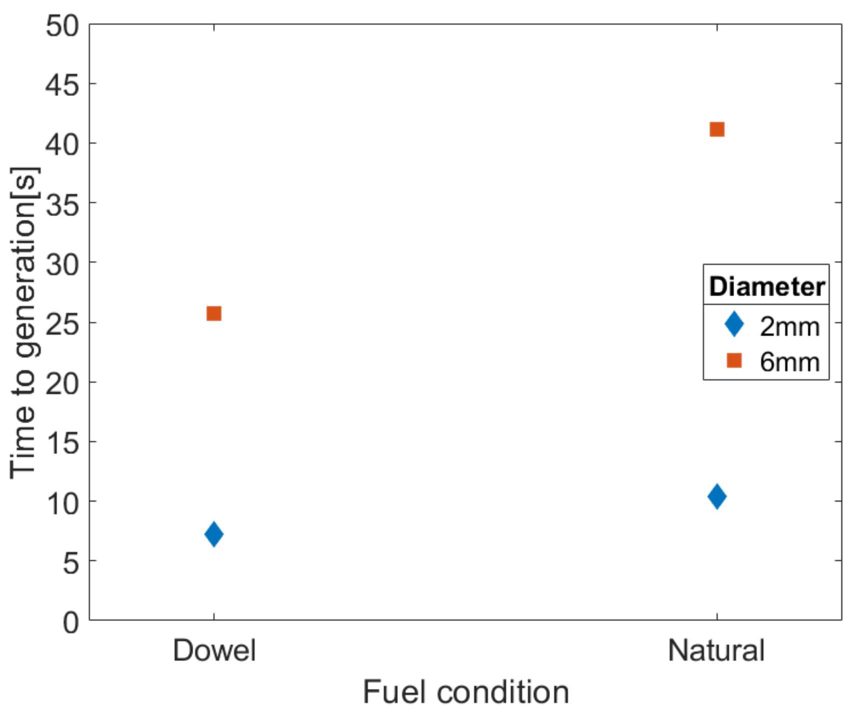

Figure 2.11: Interaction between fuel condition (natural and dowel) and diameter

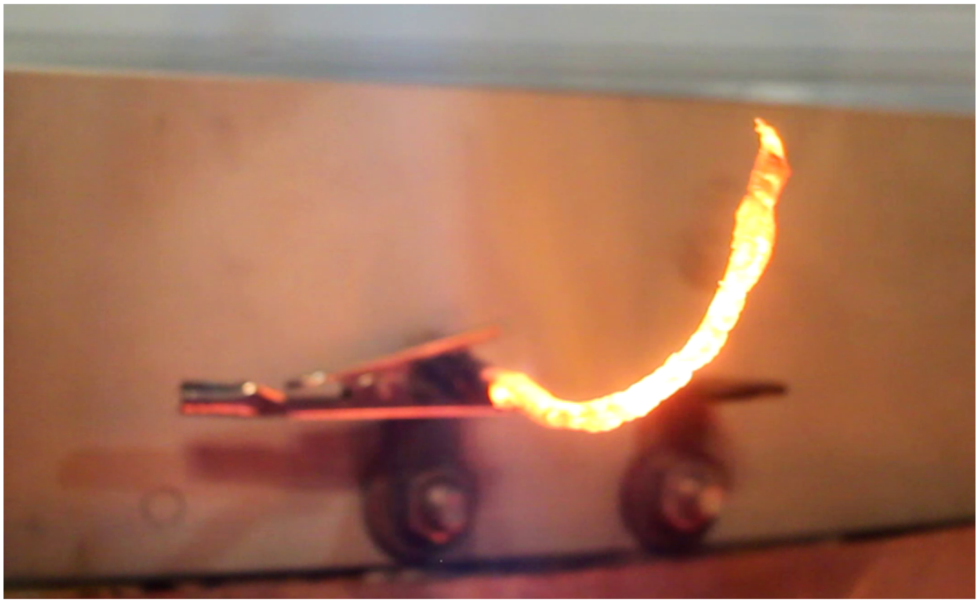

Figure 2.12: Example of natural sample deflection during testing

Figure 2.13 shows the interaction between crossflow velocity and fuel condition. Crossflow velocity does not have a significant affect on time to generation for the dowel samples (as discussed previously), but it is a significant effect for the natural samples. This is attributed to natural dowels having defects which cause significantly more drag at higher crossflow velocities.

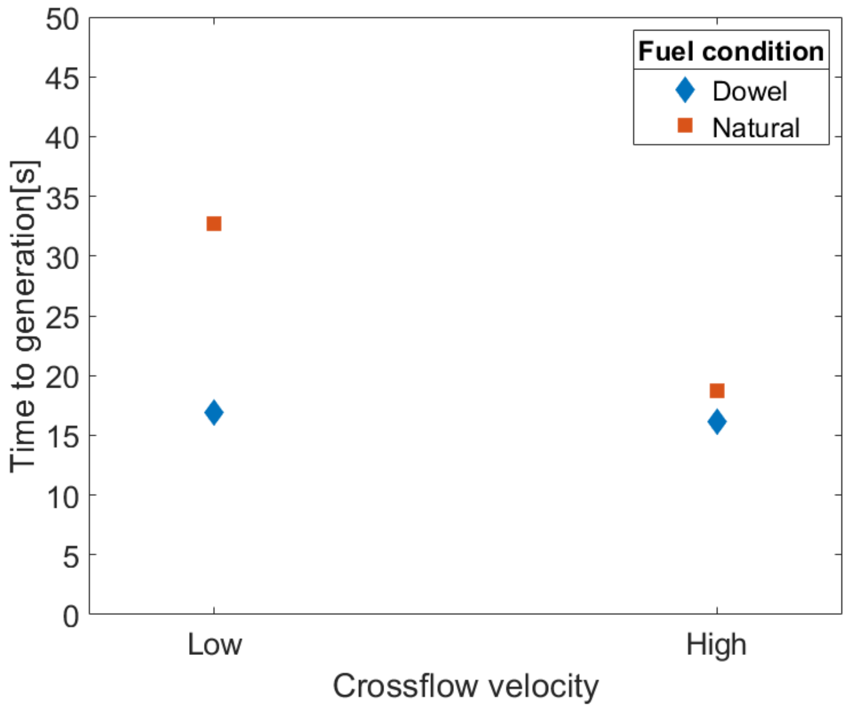

Figure 2.13: Interaction between crossflow velocity and fuel condition

2.4 Summary and Conclusions

The effects of diameter (i.e. aspect ratio), species, moisture content, fuel condition, crossflow temperature, and crossflow velocity on time required for ember generation were evaluated in this work. Visual images of the samples burning in a wind tunnel were used to determine the time required to generate embers. These times were used in a factorial study to identify which of the parameters evaluated in this work were most influential on the time to generate embers.

The specific conclusions from this work are as follows for the range of conditions evaluated:

1. The diameter of a sample has the greatest effect on the time to ember generation. As a result, it is expected that tree morphology has a significant effect on ember generation because it influences the diameter and aspect ratio of branches.

2. Bark can have a significant effect on the time required to generate an ember. Natural samples of Douglas-fir generated embers roughly 55% slower than corresponding dowel samples.

3. The time required for 2 mm samples to generate embers is relatively insensitive to moisture content, species, and crossflow velocity and is only weakly affected by fuel condition. This conclusion suggests that there exists a critical diameter below which ember generation time is nearly independent of other parameters which can influence ember formation.

2.5 Acknowledgments

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Chapter 3: Effects of Fuel Morphology on Ember Generation Characteristics at the Tree-scale

3.1 Introduction

Wildland fires are a significant hazard to people and property in the wildland-urban interface (WUI) [8], [12]. An important mechanism for fire spread near the WUI is spot fires. Spot fires are 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 lines.

Spot fires are challenging to predict, in part, because of gaps in the community's understanding of the three key processes: ember generation, transport, and deposition and ignition. The latter two aspects have arguably received the most extensive amount of research [2], [4]–[6], [8], [9], [31], [32], while less research has explored the ember generation process. Understanding ember generation and what controls it is a key step toward understanding the propensity for spot fires to occur in wildfire scenarios. This study aims to elucidate tree morphological parameters that control the ember generation process at tree-scales. To further motivate this work, current understanding about ember generation is now summarized.

The size distribution of embers provide insights into the characteristics of the branches and material that generate embers. Size and mass distributions of embers for a variety of tree sizes, species, and moisture contents have been reported in laboratory and field studies. A summary of several relevant studies is shown in Table A.2 in the Appendix. As an example of these studies, El Houssami et al. and Filkov et al. [16], [17] collected embers in trays filled with water during controlled burns at the Pinelands National Reserve. Approximately 73% of the collected embers were bark, while the rest were comprised of branches. Approximately 80% of the total firebrands had a cross sectional area less than 2 cm^2 [17]. The diameters of the cylindrical firebrands were generally between 1 and 6 mm [16]. The work just referenced, as well the results summarized in Table A.2, shows that the projected area of most embers collected during wildland fires is less than 2 cm^2.

Fire behavior can influence ember generation characteristics, including the number of embers deposited on a region (i.e., ember flux). Thomas et al. [18] conducted an ember collection study in 2016 using cameras to record the initial time, duration, and final time at which firebrands were deposited into pans filled with water during a controlled burn. Fire behavior was monitored at the same time in order to establish a correlation between fire behavior and instantaneous ember flux at a known distance downwind of the fire. They found that there was an almost direct correlation between ember flux and upwind fire intensity. Generally, a higher upwind fire intensity lead to a higher ember flux.

Identifying the "hot" embers is important to more fully assess risks of spot fires. The average projected area of "hot" embers (based on char marks left on fire resistant fabric) was measured during a series of controlled burns for the Canadian Boreal Community FireSmart Project [33]. It was observed that about 90% of the char marks on the fabric were less than 0.1 cm^2. In similar attempts to quantify "hot" embers, the size and number of holes melted through trampolines near areas with recent wildland fires have been quantified [15], [19]. In one such study, nearly 1800 holes were measured, with 85% of them having an area less than 0.5 cm^2 [15]. Embers that formed these holes were likely from a forest comprised of white fir and Jeffrey pine. In another study, 90% of the holes measured were less than 0.5 cm^2[19]. The embers that formed these holes were likely from a forest comprised of loblolly pine and yaupon. What is not fully understood from these studies is how the total number of embers that are generated (e.g., those collected in water pans) compares to those that are hot enough to ignite a fuel bed.

The crown height and moisture content of trees influences the characteristics of ember generation. Manzello et al. [20], [21] burned Douglas-fir and Korean pine trees in quiescent conditions, collected the embers, and characterized the ember size distribution. Douglas-fir trees with a 2.4 m crown height produced embers with an average diameter of 3 mm, while 4.5 m crown height trees produced embers with an average diameter of 4 mm. Trees with a moisture content higher than 70% were unable to be torched without additional heat input. It should be noted that changing crown height also changes the heat release and tree morphology (i.e., fuel loading). The size of embers collected during this work are in the same size range as embers collected during wildland fires [16]–[18]. This suggests that tree-scale studies may accurately capture physics present in a wildland fire.

At smaller scales, the diameter and density of branches and the burning conditions influence generation characteristics. Caton [14] explored the effect of various heating conditions on strength properties for several types of wooden dowels. She found that the diameter and density are key parameters that control the type of failure for each sample, but combustion characteristics (e.g., heated with hot plate vs propane flame) also influence generation. A linear relationship between dowel density and flexural strength was observed whose slope varied for different species. The fracture strength data was used to calculate a wind-induced drag force required to fracture the sample by using a simple mechanical breakage model [34]. It was predicted that dowels with a diameter of 6.35 mm (smallest diameter tested) would break when exposed to typical wildfire conditions.

Previous work by this group has identified the relative importance of fire intensity, cross-flow velocity, fuel diameter, fuel species, and fuel moisture content on the time required for ember generation at branch-scales (i.e., Chapter 2). The work was conducted by placing samples in a heated wind tunnel and quantifying the time required to fracture the sample. It was found that the diameter of the sample had the greatest effect on the time required for ember generation, with the species of the wood having the second largest effect. These findings suggest that the tree composition and morphology (which controls diameter of branches) plays a critical role in the ember generation process. It is noted, however, that the applicability of the results from branch-scale studies to tree-scales is not clear due to large differences in the time- and length-scales.

With this background and motivation, a series of tree-scale studies were study conducted where the ember generation characteristics were quantified for 108 trees. The specific objectives of this 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 a variety of species.
3. Determine the fraction of total embers generated that have sufficient energy to potentially ignite a spot fire.
4. Identify the key physical processes that control ember generation at tree-scales.

It is expected that this work will help to identify how well knowledge about ember generation characteristics at branch-scales can be extended to tree-scales and identify controlling physics that extend to forest-scales. Additionally, this work will help elucidate the relative propensity for several tree species to generate embers, and the size characteristics of those embers. Ultimately, it is hoped that knowledge from this study can be used to help create physics based models for use by wildland fire fighting personnel to better predict the likelihood of spot fire initiation.

3.2 Experimental Approach

3.2.1 Experimental Setup

Figure 3.1 shows a schematic of the outdoor testing arrangement. The arrangement consisted of a 3.1 x 1.2 m straw bed (average straw depth of 0.42 m) with the tree(s) to be torched located at one end of the bed. The bed was oriented in such a way as to keep the tree(s) downwind during typical ambient wind conditions. An industrial fan with a diameter of 1.1 m was mounted at the upwind end with a centerline height of 2.4 m. It was intended that the fan create a known crossflow velocity and direction. However, it was observed that the crossflow created by the fan was dominated by any ambient wind. The average wind speed (across the fan diameter, centered at a height of 2.4 m) produced by the fan is as follows: 1.2 m/s at the closest row of trees, 1.0 m/s at the second row, and 0.8 m/s at the farthest tree. These measurements were collected using a Kestrel 2000 Wind Meter. A weather station was used to record the local wind speed and wind direction at 30 seconds intervals during each test. This weather station malfunctioned during some of the testing, so weather data is only available for 15 of the 36 tests. The average ambient wind speed recorded by the weather station for the 15 tests was roughly 0.59 m/s.

Fire resistant fabric and aluminum trays filled with water were arranged downwind of the test section. Each small box on the schematic in Figure 3.1 indicates a fabric and tray grouped together, with approximately 1.5 m between each set and between the first row and tree #1. Each set of tray and fabric was oriented such that the tray was closer to tree #1 (labeled in Figure 3.1). The fabric pieces and trays had dimensions of approximately 0.43 x 0.40 m and 0.38 x 0.25 m, respectively. The advantage to using both fire resistant fabric and water trays is that the fabric gives information about the temperature of any embers deposited because only "hot" embers will char the fabric. Embers deposited in the water trays are immediately quenched and therefore lose any information about temperature and energy, but provide ember size information.

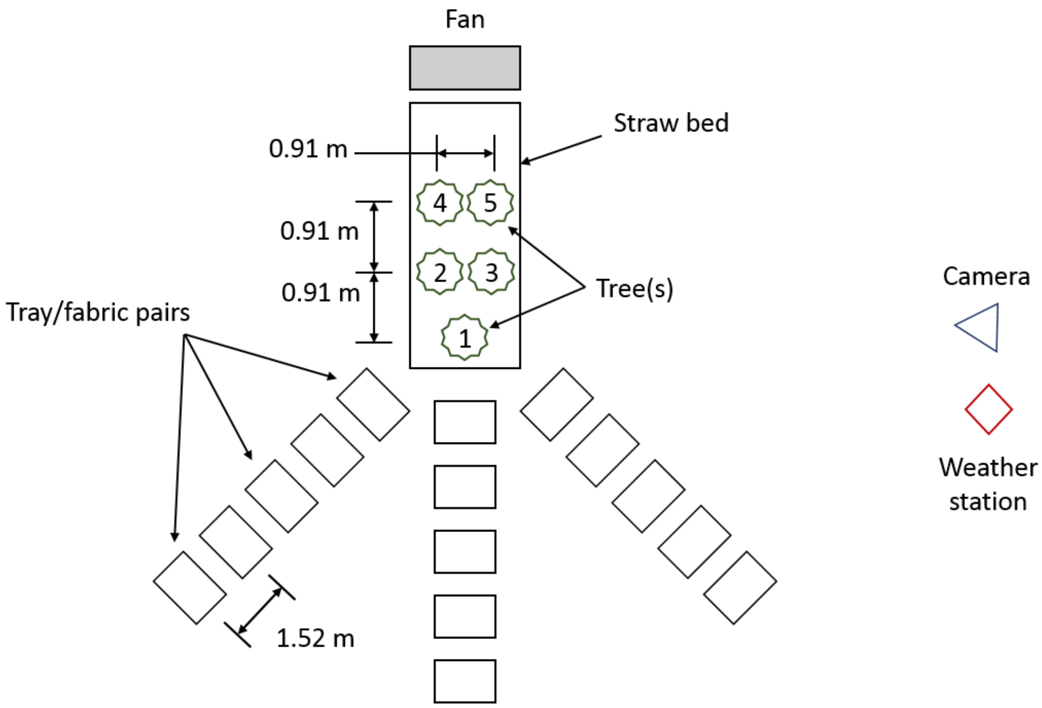


Figure 3.1: Schematic of testing setup

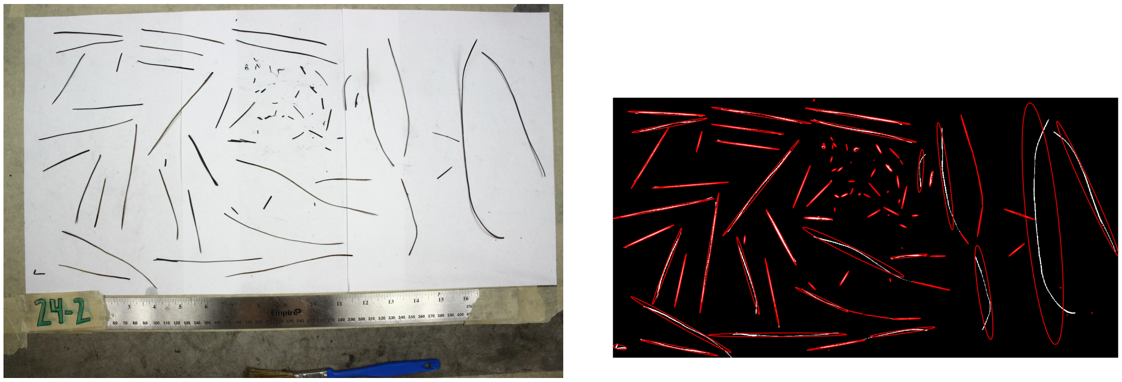
Tests were conducted with one, three, or five trees (arranged as shown in Figure 3.1) in order to vary the heat release. Three replicates of each test were performed, so a total of 108 trees burned. The species tested were Douglas-fir, grand fir, ponderosa pine, and western juniper. These species were chosen for their potential to create embers and their prevalence in the Pacific Northwest. The trees were harvested and allowed to dry outside for two to three months, depending on when the testing was conducted. Table A.3 shows the moisture content, initial mass, height, and DBH (diameter at breast height) for each tree. The average height of the trees tested was 3.7 m. Moisture content (dry basis) of the trees was measured immediately before testing by destructively sampling the trees and drying the samples in an oven at approximately 105°C until the sample weights did not change. The average moisture content at the time of testing was 21% for Douglas-fir, 29% for grand fir, 40% for western juniper, and 97% for ponderosa pine. The ponderosa pine moisture content was higher than the other species despite drying the ponderosa pine trees longer. It was decided to burn the trees even with their high moisture content because opportunities for testing outdoors were closing due to city regulations. The ponderosa pine's high moisture content is attributed to its high drought tolerance [35].

The straw bed was ignited on the upwind edge at the beginning of each test, and the fire was allowed to freely propagate to the tree. 20 $\pm$ 0.8 kg of straw was used for each test. An example image of a tree torching during a test is shown Figure 3.2. On average, torching required about 70 seconds. Juniper trees tended to have much larger flames than the other species tested.

Figure 3.2: Example of a typical test. This test had five western juniper trees.

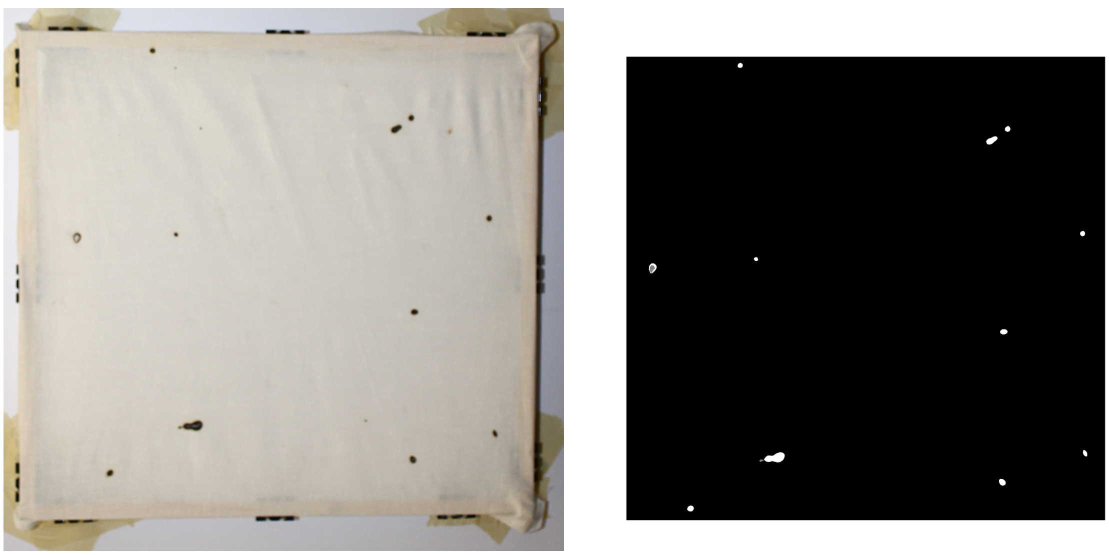
3.2.2 Data Analysis

The size and number of embers collected in the trays during testing was determined by laying the embers out on a white background and taking a high resolution image. Each image was then cropped, converted to grayscale, and binarized using an intensity threshold function in MATLAB. The number of embers was determined by counting groups of connected pixels. The area per ember was determined by counting number of pixels per object, and converting that number of pixels to an area using the pixel resolution. The pixel length was calculated using a known distance in each image (a standard ruler). The resolution for the images of embers was 0.11 mm per pixel, and 0.13 mm per pixel for the fabric images. Ember length was determined by modeling each object as an ellipse using a multivariate normal distribution; the major axis of each ellipse was assumed to be the ember length. The ember diameter was then determined to be the ember area divided by length (assuming each ember had a rectangular cross section). The same technique was used to process the fire resistant fabric that received char marks. Figure 3.3 shows an example of the analysis for the embers collected in one tray, and Figure 3.4 shows an example of the binarization for a piece of fabric. The red ellipses overlaid on Figure 3.3(b) show the multivariate normal distribution predicted for each ember. Several embers would have a qualitatively poor fit for ember diameter if the diameter was assumed to be the minor axis of the ellipse, but recall that the ember diameter is determined by dividing the ember area by the length. This provides more reasonable diameters than if the minor axis of the ellipse was used. Another source of error for the fabric images is when char marks overlap. The analysis code used assumes any connected group of pixels is one char mark, even though it can be two or more overlapping marks. In order to roughly quantify the possible error in ember and char mark counts, the number of embers or char marks was counted by a person for six images (three for ember and three for char marks). Table 3.1 shows the calculated and counted values for the images. Generally, calculated values were within 12% of counted values. The calculated ember counts tended to be slightly higher than when counted by hand, while the calculated char mark counts were slightly lower than when counted manually.



(a) (b)

Figure 3.3: Example original image and binarized image with fit ellipses of collected embers.



(a) (b)

Figure 3.4: Example original image and binarized image of char marks.

For two tests with juniper trees, the tree(s) burned intensely enough to fully char pieces of fabric in the row closest to tree # 1, destroying the data about "hot"

Table 3.1: Number of embers and char marks as counted by script or person

Tray/fabric	**Object type**	**Script**	**Person**	**Script/person 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

embers from five pieces of fabric. The fabric data from tests with similar conditions and number of trees was used as a rough estimate for the missing data, instead of neglecting data from these locations all together and systematically biasing the results low. Specifically, data from test number 23, trays 01 and 02 was replaced with data from test number 21, trays 01 and 02. Similarly, data from test number 30, trays 01, 02, and 03 was replaced with data from test number 33, trays 01, 02, and 03. While not ideal, not substituting the data would have severely underestimated the number of embers generated from western juniper trees. All other trends (e.g., ember average area, diameter, and aspect ratio) were not significantly changed by replacing the missing data.

All mass and mass loss values reported have been corrected for moisture content. This was done using the following relationship:

$$wood\ mass = \frac{total\ mass}{1 +\ moisture\ content} \tag{3.1}$$

where moisture content is represented as a percentage.

No correlations of ember generation with respect to wind conditions are described in this paper because there were not enough data to confidently report trends and dependencies. Also, the wind speeds that were recorded were relatively low (i.e., 0.59 m/s), and as a result are expected to only have secondary effects. The authors recognize that wind speed and direction may have a significant role in the generation and transport of embers. Nonetheless, it is believed that the work described in this study contributes to the community's understanding of the physics governing ember generation in wildland fires neglecting wind effects.

3.3 Results and Discussion

This section begins with an exploration of ember and char mark flux with respect to distance and mass loss per test. Then, the total number of embers and char marks per kilogram of mass loss are plotted as a function of species and the average ember aspect ratio. Next, the relationship between ember aspect ratio and distance is highlighted. Finally, two multiple variable regression models are created using the number of embers and char marks generated per test as the response variables.

Figure 3.5 shows the average ember flux as a function of distance relative to the closest tree (i.e., location 1 in Figure 3.1). All references to distance are with respect to this location. A quadratic-like decay in ember flux as the distance increases is observed. This dependence is expected because the area that an ember can land in increases as the square of radius. It is observed that there is a large species dependence of the ember flux relatively close to the tree(s) (i.e., within 3 m). Ponderosa pine generates the fewest number of embers with roughly one-third as many embers as grand fir and western juniper at 1.52 m from the closest tree. As the distance increases, the difference in ember flux between species rapidly decreases.

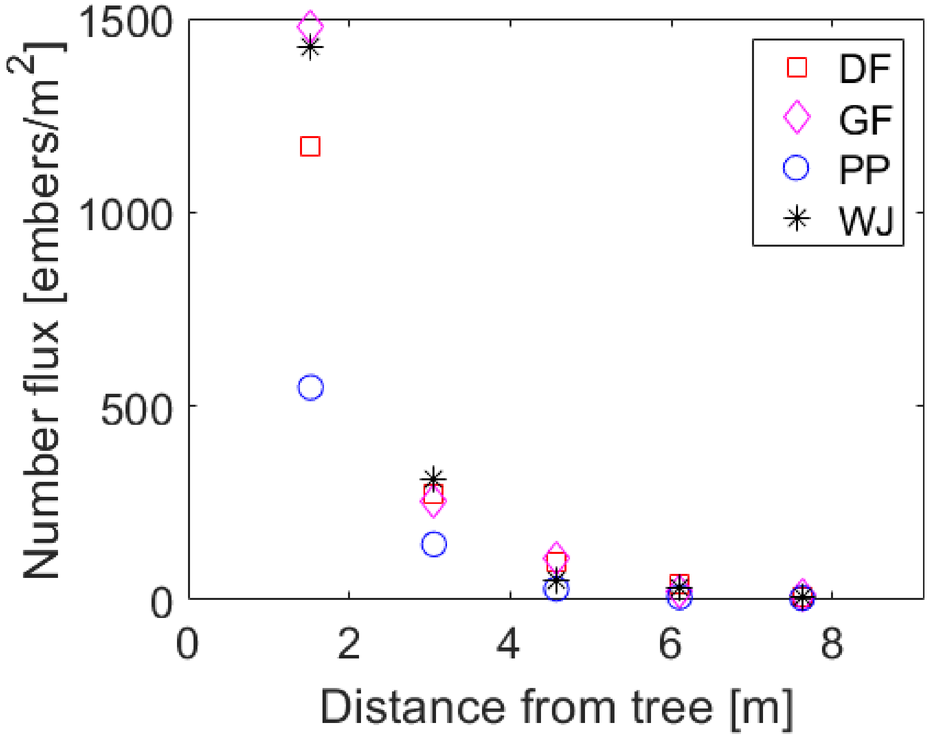


Figure 3.5: Average ember flux per test with respect to distance from the closest tree. Precision uncertainties for these data are shown in Figure B.1.

As a comparison to the ember flux, Figure 3.6 shows the average char mark flux per test as a function of distance. The reader should note that "ember" refers to physical material collected in the trays filled with water, while "char mark" refers to the black marks left on the fire resistant fabric by hot embers (see Figure 3.4(a) for an example). Several differences are observed in the trends for ember fluxes and char mark fluxes. The highest number flux for char marks was roughly one-third of the highest number flux for embers, showing that most of the embers generated are not capable of leaving char marks. Grand fir generated the largest ember flux at 1.52 m, but not the highest char mark flux at the same distance. Instead, western juniper generated the highest char mark flux at 1.52 m. Beyond 6 m, Douglas-fir, grand fir, and ponderosa pine generated char mark fluxes of 0-6 char marks/m^2, while western juniper generated a char mark flux of roughly 15 char marks/m^2.

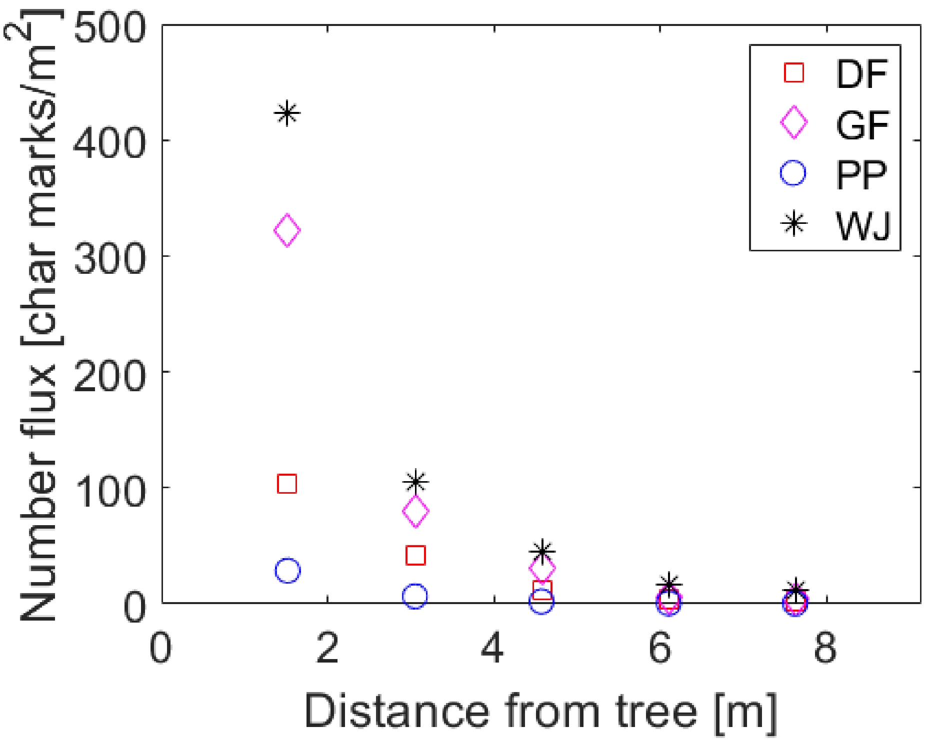


Figure 3.6: Average char mark flux per test with respect to distance from the closest tree. Precision uncertainties for these data are shown in Figure B.2.

The total ember flux was plotted relative to the total mass loss for each test to identify the fraction of fuel that was burned and formed embers, and is shown in Figure 3.7. In general, the ember flux increases with increasing mass loss for ponderosa pine and western juniper. In contrast, no such relationship is apparent for Douglas-fir and grand fir. It is plausible that the different responses of ember generation to mass loss relate to differences in the propensity of embers to be consumed near the trees. Generally, western juniper experienced the highest total mass loss per test, followed by Douglas-fir and grand fir. Ponderosa pine tended to have the lowest mass loss per tests. These trees did not burn as readily as the others, and this may be attributed to a lower fuel loading and higher moisture content. The high mass loss of the western juniper may be attributed to the observation that western juniper tended to have the highest initial mass and produced the largest flames, qualitatively. Initial mass and mass loss values for each tree are reported in Table A.3.

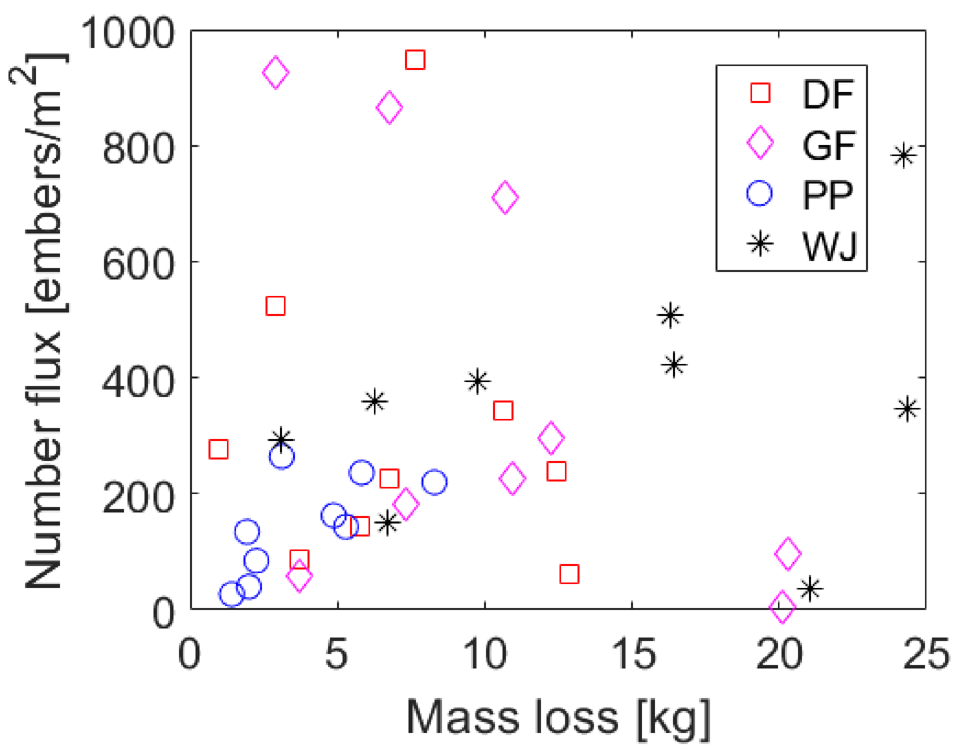


Figure 3.7: Ember flux with respect to mass loss per test

As a comparison to the ember flux shown previously, Figure 3.8 shows the char mark flux as a function of total mass loss per test. Generally, trends between char mark flux and mass loss are similar to trends between ember flux and mass loss. Specifically, the char mark flux tends to increase with increasing mass loss for western juniper, but no relationship is apparent between mass loss and char mark flux for the ponderosa pine. Also note that the same tests that were outliers in Figure 3.7 tend to be outliers in Figure 3.8. Notice that the peak char mark flux is roughly one-quarter of the peak ember flux. This is evidence that the majority of embers collected are not hot enough to char the fabric, and thus unlikely to initiate a spot fire.

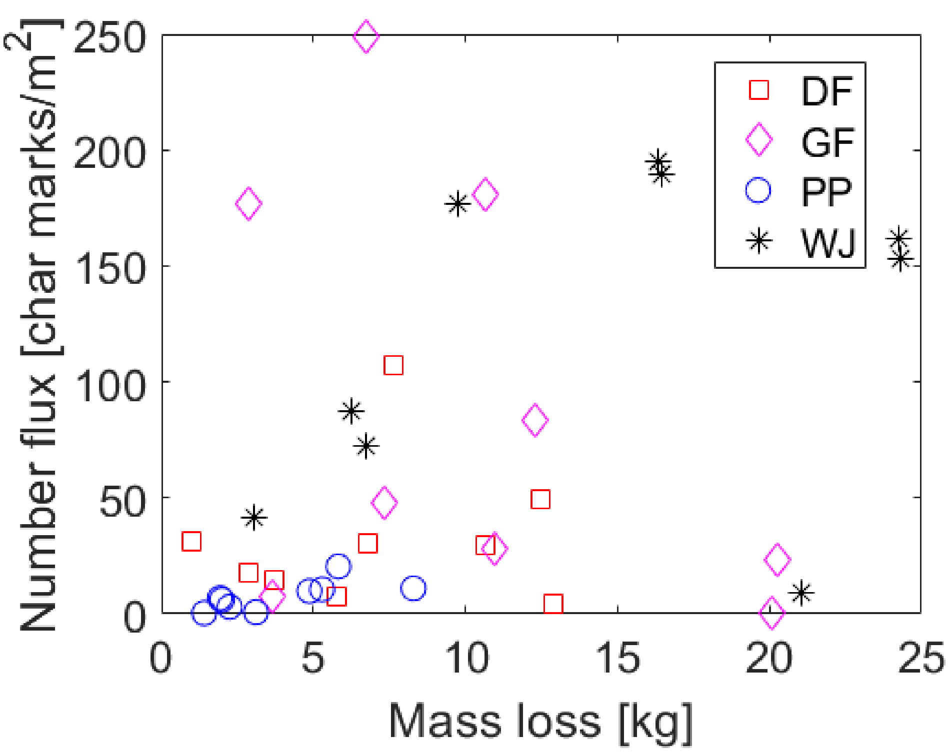


Figure 3.8: Total char mark flux with respect to total mass loss per test

In order to visualize the size distribution of the embers, Figure 3.9 shows the diameter and length of each ember collected. Embers from Douglas-fir, grand fir, and western juniper generally have similar diameters and lengths. In contrast, ponderosa pine has a much larger spread of ember lengths, and a smaller spread of ember diameters. The average areas of the embers generated from Douglas-fir, grand fir, and western juniper are all comparable: 15.3, 14.4. and 10 mm^2, respectively. Ponderosa pine, however, has a significantly larger average area (32.5 mm^2). Generally, the ember areas for this study are smaller than previous work. Manzello et al. [20] collected embers with an average area 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 may be caused by differences in the experimental arrangement (e.g., method of tree ignition and size of filter used to screen embers).

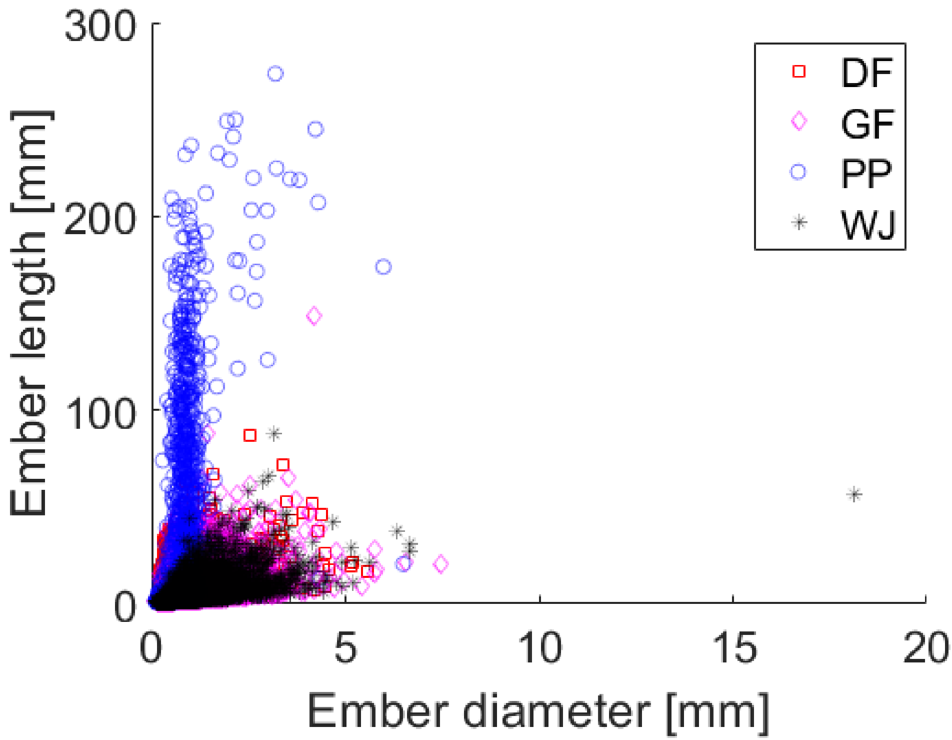


Figure 3.9: Diameter and length of all embers collected

Figure 3.10 shows the diameter and length of every char mark collected. Generally, the char marks for Douglas-fir, grand fir, and western juniper have a greater area than their respective embers, with the char marks having areas between 50.2 and 63.8 mm^2. The average ember and char mark areas for each species are shown in Table 3.2. The observation that the average char mark areas are larger than the respective ember areas is attributed to heat spreading across the fabric. Western juniper has largest average char mark area, while having the smallest average ember area. This is attributed to the qualitative observation that western juniper embers that were hot enough to leave char marks tended to be mostly ash at the conclusion of each test. This suggests a more complete combustion than embers from the other species, and thus more energy transfer into the fabric. The average char mark area for ponderosa pine is roughly 11 mm^2, which is smaller than the average area of embers generated by ponderosa pine. This observation, along with observations of char mark flux, suggest that ponderosa pine is the least likely to initiate a spot fire of the species tested. It should be noted that the fabric used in this study has not been fully characterized (i.e., the relationship between char mark area and ember energy upon deposition is not fully understood), and thus any relationship between char mark area and spot fire ignition is speculative. Previous work that used fire resistant fabric to collect embers observed that 90% of char marks had an area less than 10 mm^2 [33]. It is plausible that the larger size of char marks in this study results from the relatively close proximity of the fabric to the location where the embers were generated. The embers from the prior study traveled farther (i.e., between 10.5 and 11.7 m), and thus had more time to combust before deposition. There may also be physical or chemical differences in the fire resistant fabric used in this study and the previous study that affect the amount of heat required to leave a char mark.

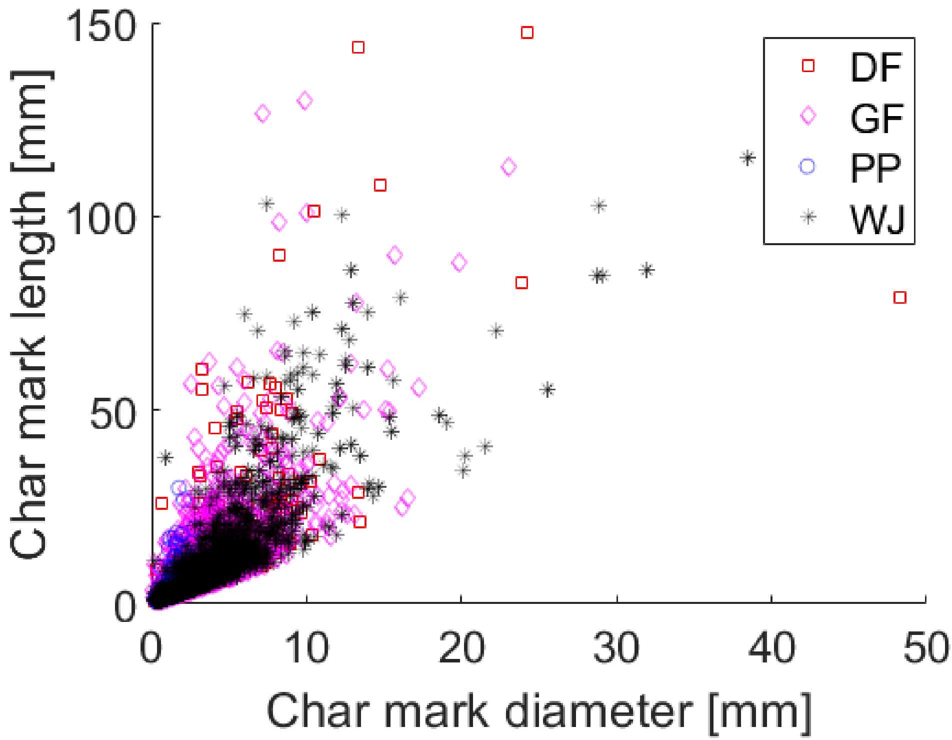


Figure 3.10: Diameter and length of all char marks collected

The total number of embers and char marks generated per kilogram of tree burned for all tests is plotted for each species of tree in Figure 3.11 in order to account for the differences in mass loss between species. Each data point represents the data from all tests for a given species (i.e., each point accounts for the total embers or char marks generated and total mass loss). Douglas-fir generated the most embers per kilogram of fuel consumed, while western juniper generated the fewest (65 and 37 embers/kg, respectively). Ponderosa pine and grand fir produced roughly the same number of embers per kilogram mass loss at roughly 52 embers/kg. When considering "hot" embers, grand fir and western juniper generated the highest number of char marks per kilogram of mass loss, with a generation of about 22 char marks per kilogram. Ponderosa pine generated approximately 5 char marks per kilogram, which is the fewest of the species tested (all values are shown in Table 3.2). Figure 3.11 also shows the ratio of total char marks to total embers collected over all the tests. Western juniper has the largest char/ember ratio of roughly 60%, which indicates that western juniper generated the highest fraction of "hot" embers of all the species tested. Ponderosa pine generated the lowest fraction of "hot" embers, with only roughly 10% of the total embers collected being hot enough to leave char marks.

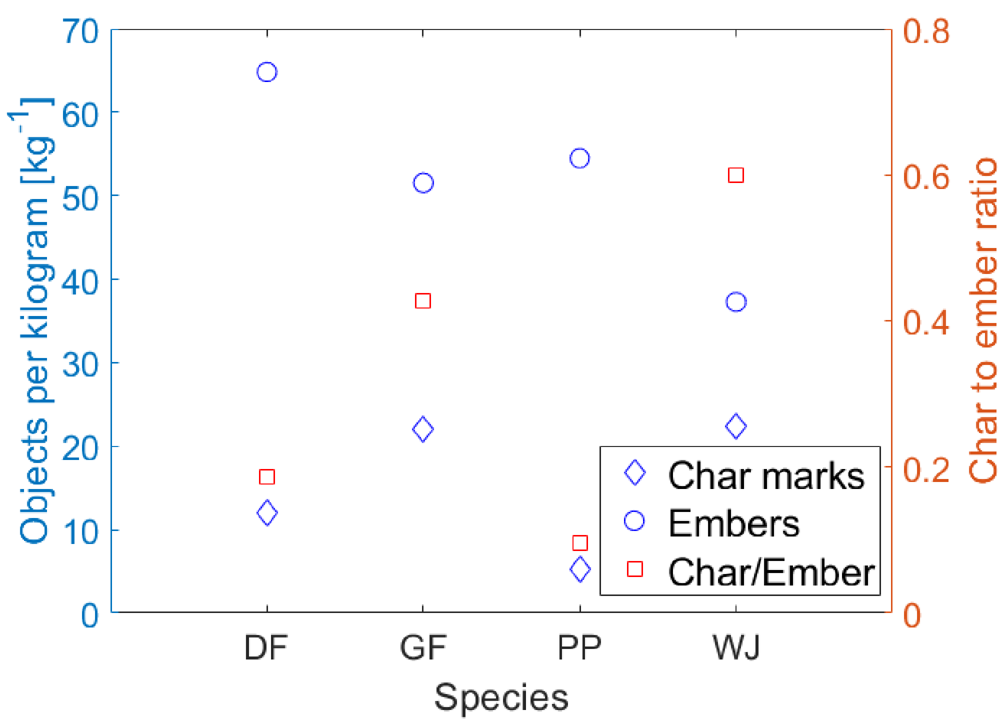


Figure 3.11: Total number of embers and char marks generated per kilogram of mass loss with respect to species

Previous research by this group has suggested that ember aspect ratio is a significant parameter governing ember generation at branch-scales. To evaluate the significance of this parameter at tree-scales, the total number of ember and char marks per kilogram of mass loss was plotted relative to the average ember aspect ratio for each species in Figure 3.12 (from left to right: western juniper, grand fir, Douglas-fir, and ponderosa pine). Several observations can be made. First, it is observed that there is a roughly exponential decay relationship between char/ember fraction and average ember aspect ratio. These results mean that the larger the ember aspect ratio, the lower the fraction of total embers generated that are "hot" enough to leave char marks on the fire resistant fabric. Second, the total char marks collected per kilogram decreases with respect to aspect ratio. Third, the number of embers collected per kilogram of mass loss tends to increase with an increasing aspect ratio, except for the highest aspect ratio. It is hypothesized that more embers being generated at a higher ember aspect ratio is due to the crossflow induced drag and bending stress of a needle/branch increasing as the length/aspect ratio increases, and thus increasing the likelihood of ember generation.

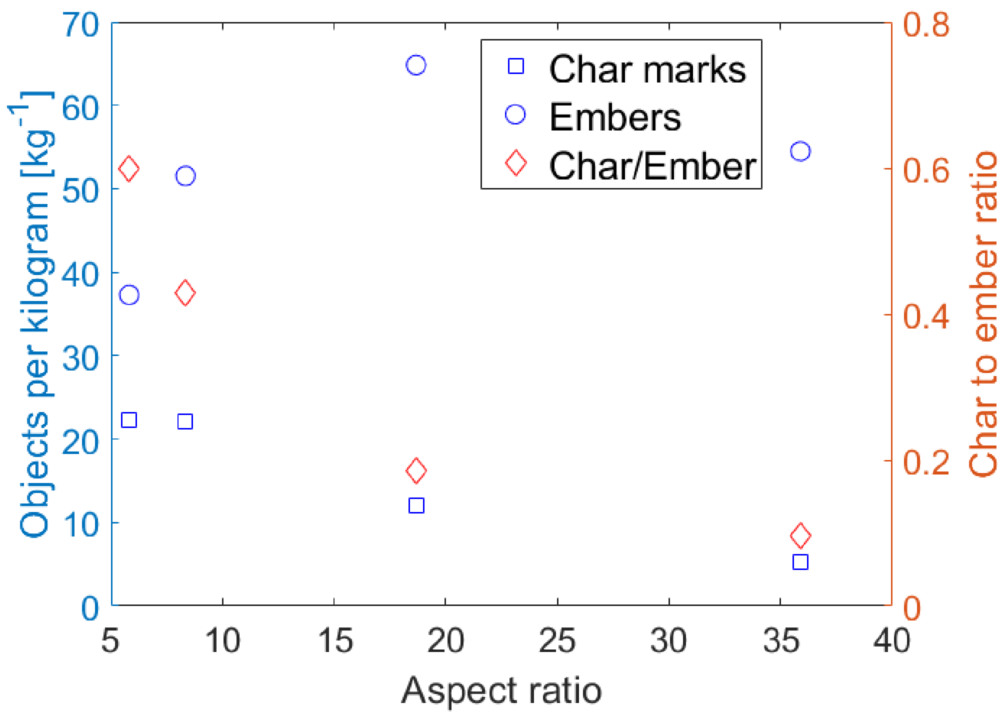


Figure 3.12: Total number of embers and char marks generated per kilogram of mass loss with respect to average ember aspect ratio

Table 3.2: Average area and counts per mass loss of embers and char marks for all species tested

Species	Ember area [mm^2]	Char mark area [mm^2]	Embers/kg	Char marks/kg
Douglas-fir	15.3	55.5	64.8	12.1
Grand fir	14.4	50.2	51.5	22.1
Ponderosa pine	32.5	11.3	54.5	5.2
Western juniper	10	63.8	37.3	22.3

To better understand how the physical characteristics of embers evolve during their transport, the average aspect ratio of embers collected as a function of distance is shown in Figure 3.13. The error bars shown in Figure 3.13 are precision uncertainty. Uncertainty is shown in this figure because each data point represents the average of the aspect ratios for all embers collected at that distance, and the number of embers collected at each point is not constant. At the larger distances, the large uncertainty in the ponderosa pine aspect ratio is likely due to the observation that few ponderosa embers were collected. Generally, the aspect ratios for Douglas-fir, grand fir, and western juniper stay relatively constant with respect to distance. This suggests that the aspect ratio of an ember does not affect the distance it travels for the conditions and distances in this work. The high aspect ratio for ponderosa pine at the closest distance may be explained by the obervation that many unburned needles fell into the trays. Unburned needles tend to be longer than burned needles, which would increase the apparent aspect ratio.

A multiple variable, linear regression was performed to determine the relative importance of the number of trees (which influences heat release), average moisture content, mass loss, average ember aspect ratio, and fuel species on the number of char marks and the number of embers per test. Regression models for both embers and char marks have p-values of less than 0.05, signifying that the models significantly account for variance in the response. The combination of source terms (with p-values) shown in Tables 3.3 and 3.4 generate models with the highest adjusted R^2 values of all combinations tested, despite having several terms with p-values greater than 0.05. The adjusted R^2 values for the ember and char mark models are 65% and 42%, respectively.

Several observations can be made from these regression models. First, the tree

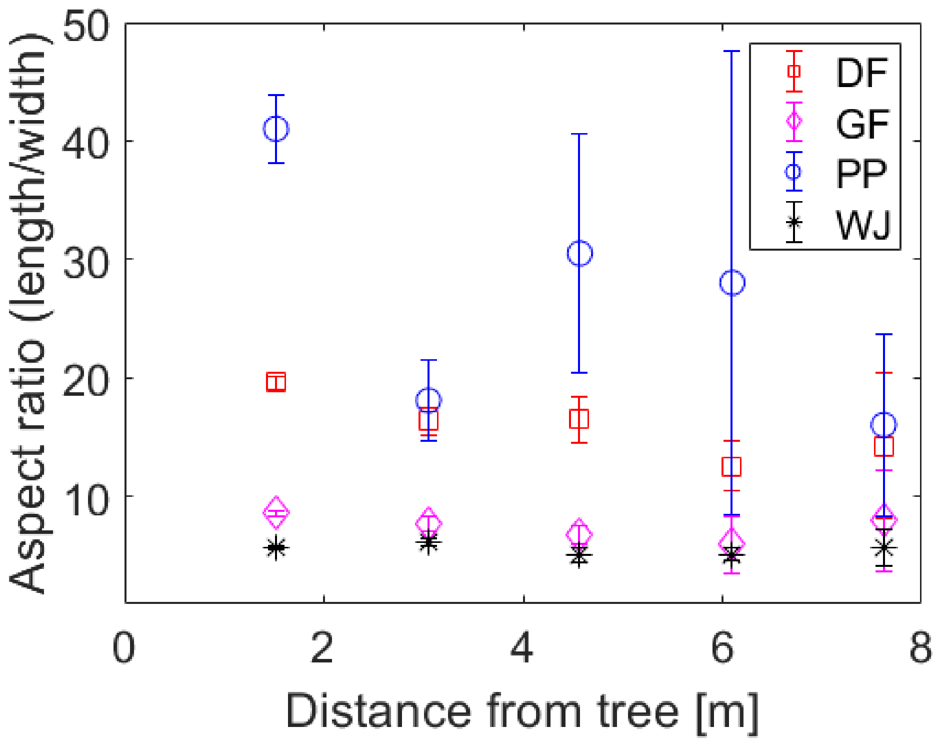


Figure 3.13: Average ember aspect ratio with respect to distance

species is the most significant single-term parameter in both models, with p-values of 0.003 and 0.009 in Tables 3.3 and 3.4, respectively. This means that the fuel species is the parameter that has the largest effect on the number of embers and char marks generated per test. This is consistent with the large differences in ember and char mark flux between species observed in Figures 3.7 and 3.8. The second observation is that the number of trees, mass loss, and ember aspect ratio all have a similar probability of affecting the number of embers generated based on their p-values of 0.335, 0.323, and 0.358, respectively. Moisture content is least likely to influence the number of embers generated because it's p-value is higher (0.421). Conversely, moisture content is the parameter (excluding species) most likely to influence the number of char marks generated with a p-value of 0.29. This is attributed to moisture content having a significant affect on the time to ignition of fuels [36]. Mass loss and ember aspect ratio are the single-term parameters least likely to affect the number of char marks because of their relatively high p-values (0.862 and 0.917, respectively).

The observation that species and total mass loss are the parameters most likely to influence the number of embers generated suggests that tree morphology is critical to predicting ember generation because that controls the number of needles that can break off (i.e., fuel loading). The species and moisture content are the two parameters most likely to affect the number of char marks created, which suggests that the physical properties of an ember (i.e., density, heat capacity, and shape) are important in predicting how many "hot" embers will be generated. It also indicates that seasonal variation of moisture content and/or fire intensity (which influences fuel moisture content) may alter the propensity to generate "hot" embers. The number of trees is likely to affect both the number of embers and char marks generated, which implies that heat release plays an important role in both processes.

Table 3.3: Analysis of variance for multiple regression of ember count

Source	**Degrees of freedom**	**Adj. sum of squares**	**Adj. mean squares**	**F-Value**	**P-Value**
Regression	15	3333782	222252	2.69	0.02
# of trees	1	80513	80513	0.97	0.335
Moisture content	1	55760	55760	0.67	0.421
Mass loss	1	84850	84850	1.03	0.323
Ember AR	1	73048	73048	0.88	0.358
Species	3	1587479	529160	6.4	0.003
Mass loss*Mass loss	1	12811	12811	0.16	0.698
Mass loss*Ember AR	1	430969	430969	5.21	0.033
# of trees*Species	3	1017045	339015	4.1	0.02
Ember AR*Species	3	1453906	484635	5.86	0.005
Error	20	1652953	82648		
Total	35	4986735			

Table 3.4: Analysis of variance for multiple regression of char mark count

Source	**Degrees of freedom**	**Adj. sum of squares**	**Adj. mean squares**	**F-Value**	**P-Value**
Regression	15	1022625	68175	5.36	0.00
# of trees	1	11829	11829.4	0.93	0.346
Moisture content	1	15038	15038.5	1.18	0.29
Mass loss	1	396	395.8	0.03	0.862
Ember AR	1	142	141.9	0.01	0.917
Species	3	195488	65162.5	5.12	0.009
Mass loss*Mass loss	1	16833	16832.6	1.32	0.264
Mass loss*Ember AR	1	30673	30672.5	2.41	0.136
# of trees*species	3	297528	99175.9	7.8	0.001
Ember AR*Species	3	140014	46671.3	3.67	0.03
Error	20	254382	12719.1		
Total	35	1277007			

3.4 Summary and Conclusions

In this work, embers and char marks from a series of tests involving the torching of Douglas-fir, grand fir, ponderosa pine, and western juniper trees were collected. Groups of trees (1, 3, or 5 trees depending on the test) were arranged in a bed of straw, with sets of trays filled with water and fire resistant fabric downwind. A total of 27 trees were burned for each species. "Hot" embers were differentiated from total embers by char marks left on fire resistant fabric. Ember and char mark size characteristics were determined from a computer script using images of the collected embers and char marks.

The specific conclusions for this work are as follows:

1. The species of the tree has a more significant effect on the number of embers generated than the other parameters measured (number of trees, moisture content, mass loss, and ember aspect ratio). This is evidenced by the p-value

for species in the regression model for ember counts being the lowest of all the variables. Grand fir and western juniper generated the most total embers, with approximately 4900 and 4800 embers generated, respectively. Ponderosa pine generated roughly 1900 embers, which was the fewest of any species.

2. The species of the tree has a more significant effect on the number of char marks generated by "hot" embers than the other parameters measured (number of trees, moisture content, mass loss, and ember aspect ratio). This is supported by the low p-value for speces in the char mark regression model. Western juniper produced the most char marks, with roughly 2900 char marks produced. Ponderosa pine generated the fewest char marks, generating approximately 200 char marks.

3. In general, roughly one-third of the total embers collected were hot enough to leave char marks. It was observed that western juniper had the highest percentage of "hot" embers with approximately 60% of the total embers being hot enough to leave char marks. Ponderosa pine had the lowest portion of "hot" embers, with roughly 10% of the embers generated being hot enough to leave char marks. This suggests that the fraction of "hot" embers generated is species dependent.

4. Douglas-fir was shown to generate the most embers per kilogram of mass loss, followed by ponderosa pine, with roughly 65 and 55 embers/kg, respectively. Western juniper generated the fewest embers per kilogram, generating 37 embers/kg. Grand fir and western juniper had comparable char mark fluxes per

kilogram (roughly 23 char marks/kg), and were the highest of the species tested.

3.5 Acknowledgements

Ryan Bray, Cole Haxton, and Alan Tursunbaev were instrumental in the experimental setup and data collection. We are extremely grateful for the assistance of Steve Pilkerton and the OSU Research Forests for providing trees. We also thank Brooke and Andy Grey with The Nature Conservancy for providing trees and access to a controlled burn. This research was enabled by funding from the Joint Fire Science program (project number 15-1-04-9).

Chapter 4: Summary and Conclusion

This work sought to elucidate key parameters governing the ember generation process during wildland fires. This was done using a multiple scale approach. The first study consisted of burning samples in a heated wind tunnel to determine which parameters have the greatest influence on time required to generate an ember. The second study sought to elucidate ember generation characteristics from different fuel species by torching trees.

At the branch-scale, a 2^k factorial study was conducted to determine the relative importance of crossflow temperature, crossflow velocity, fuel diameter, fuel species, and fuel moisture content on the time required for ember generation. A subset of the data was used to elucidate any differences between manufactured dowels and natural samples. It was observed that the diameter of the sample has the greatest effect on the time to ember generation. The second greatest effect was from the sample species. For the 2 mm samples, the moisture content, species, and crossflow velocity have little affect on the time to generation. This suggests that there exists a critical diameter below which time to ember generation is nearly independent of the other parameters tested. Bark may have a significant effect on the time to ember generation, as evidenced by the observation that natural samples generated embers roughly 55% slower than their manufactured dowel counterparts.

For the tree-scale study, a total of 108 trees were torched, and the embers generated were collected using trays filled with water and fire resistant fabric. It was observed that both the ember flux and char mark flux were significantly dependent on the species of tree being torched. Douglas-fir generated the most embers per kilogram of fuel consumed; western juniper generated the fewest. Roughly 60% of the embers generated by western juniper were hot enough to char the fabric, while only 10% of the embers generated by ponderosa pine were hot enough. Overall, approximately one-third of the total embers generated were hot enough to leave char marks.

Across the two scales evaluated, the fuel morphology was shown to significantly affect the ember generation process. At the branch-scale, the species and diameter (i.e., fuel morphology) were shown to be the two parameters that had the greatest affect on the time required for an ember to generate. At the tree-scale, the fuel species was the parameter that had the most significant affect on the number of embers and char marks generated. Each species has a different fuel loading and needle/branch characteristics. This supports the branch-scale observation that the diameter plays a significant role in the ember generation process.

Chapter 5: Future work

Several avenues of future work have been considered for the branch-scale. One, more natural samples of various species (such as grand fir and ponderosa pine) can be tested with the same experimental approach described in this work to better understand the differences between dowels and natural samples. Do natural samples of different species behave similarly with respect to time required to generate embers? Two, thermogravimetric analysis and differential scanning calorimetry can be used to help elucidate the differences between natural and dowel samples. Samples consisting of entirely of bark can be compared to samples made up of the entire branch (i.e., bark, sapwood, and heartwood). Three, more samples with diameters between 2 and 6 mm can be tested with the same experimental approach described in this work to help identify the affect diameter has on the time to generation.

There are several areas of potential future work for the tree-scale as well. One, tests can be conducted with trays and fabric arranged completely around the trees, instead of only on one side. This would allow for a more complete capture of embers. Detailed wind speed and direction measurements would allow for wind's affect on ember generation to be better characterized. Two, an infrared camera can be used to visualize embers immediately after their generation to provide an estimate of ember flux and size. This can then be compared to the total number of embers and char marks collected to determine the fraction of embers that travel downwind.

An experimental setup similar to the tree-scale setup could be used to test the effectiveness of different fire retardants. The number of embers and char marks generated from trees without the fire retardant could be compared to the number generated from trees with the fire retardant as a metric of the retardant's effectiveness.

Chapter 6: References

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APPENDICES

Appendix A: Tables

Table A.1: Average time to generation and standard deviation for all manufactured dowel tests. Each test had at least three replicates.

Diameter [mm]	Species	Moisture content	Heat Intensity	Crossflow	Time [sec]	STDDEV [sec]
2	Douglas-fir	15%	high	high	6.6	0.7
6	Douglas-fir	15%	high	high	24.1	1.9
2	Juniper	15%	high	high	7.6	1.1
6	Juniper	15%	high	high	49.1	6.2
2	Ponderosa	15%	high	high	8.0	0.3
6	Ponderosa	15%	high	high	24.4	2.5
2	White oak	15%	high	high	5.3	1.0
6	White oak	15%	high	high	42.2	2.8
2	Douglas-fir	Dry (0%)	high	high	4.2	2.3
6	Douglas-fir	Dry (0%)	high	high	21.8	4.3
2	Juniper	Dry (0%)	high	high	8.7	2.1
6	Juniper	Dry (0%)	high	high	28.7	7.3
2	Ponderosa	Dry (0%)	high	high	6.2	0.2
6	Ponderosa	Dry (0%)	high	high	22.5	1.3
2	White oak	Dry (0%)	high	high	5.2	1.1
6	White oak	Dry (0%)	high	high	36.2	4.2
2	Douglas-fir	15%	low	high	10.1	1.2
6	Douglas-fir	15%	low	high	28.5	0.7
2	Juniper	15%	low	high	9.8	1.4
6	Juniper	15%	low	high	48.3	3.9
2	Ponderosa	15%	low	high	7.0	0.4
6	Ponderosa	15%	low	high	26.7	1.2
2	White oak	15%	low	high	6.5	1.2
6	White oak	15%	low	high	48.2	1.0
2	Douglas-fir	Dry (0%)	low	high	8.8	0.7
6	Douglas-fir	Dry (0%)	low	high	24.6	2.1
2	Juniper	Dry (0%)	low	high	7.1	1.3
6	Juniper	Dry (0%)	low	high	41.3	11.3
2	Ponderosa	Dry (0%)	low	high	6.6	0.2
6	Ponderosa	Dry (0%)	low	high	23.5	1.0
2	White oak	Dry (0%)	low	high	7.5	0.0
6	White oak	Dry (0%)	low	high	38.9	2.7
2	Douglas-fir	15%	high	low	6.2	2.3
6	Douglas-fir	15%	high	low	27.2	5.4
2	Juniper	15%	high	low	7.1	2.4

Diameter [mm]	Species	Moisture content	Heat Intensity	Crossflow	Time [sec]	STDDEV [sec]
6	Juniper	15%	high	low	38.1	13.0
2	Ponderosa	15%	high	low	7.7	0.2
6	Ponderosa	15%	high	low	29.6	1.1
2	White oak	15%	high	low	6.0	1.4
6	White oak	15%	high	low	53.9	7.6
2	Douglas-fir	Dry (0%)	high	low	8.9	0.9
6	Douglas-fir	Dry (0%)	high	low	23.5	4.4
2	Juniper	Dry (0%)	high	low	8.0	1.3
6	Juniper	Dry (0%)	high	low	40.6	8.4
2	Ponderosa	Dry (0%)	high	low	7.8	0.2
6	Ponderosa	Dry (0%)	high	low	22.5	0.9
2	White oak	Dry (0%)	high	low	7.5	2.6
6	White oak	Dry (0%)	high	low	44.7	16.5
2	Douglas-fir	15%	low	low	5.3	1.2
6	Douglas-fir	15%	low	low	28.4	9.8
2	Juniper	15%	low	low	7.9	0.9
6	Juniper	15%	low	low	40.3	9.9
2	Ponderosa	15%	low	low	8.0	0.4
6	Ponderosa	15%	low	low	40.7	7.5
2	White oak	15%	low	low	5.3	2.7
6	White oak	15%	low	low	52.1	5.9
2	Douglas-fir	Dry (0%)	low	low	7.5	1.6
6	Douglas-fir	Dry (0%)	low	low	27.8	6.4
2	Juniper	Dry (0%)	low	low	5.4	0.6
6	Juniper	Dry (0%)	low	low	45.5	13.3
2	Ponderosa	Dry (0%)	low	low	8.9	0.7
6	Ponderosa	Dry (0%)	low	low	35.8	7.1
2	White oak	Dry (0%)	low	low	5.2	2.1
6	White oak	Dry (0%)	low	low	46.3	6.2

Table A.2: Previous ember collection experiments

Author	Site Description	Collection Method	Ember Size Distribution
Manzello et al. [21]	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. [20]	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. [20]	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. [15]	2007 Angora fire, White Fir and Jeffrey Pine with a heavy understory	Trampoline	85% less than 0.5 cm^2
El Houssami et al. [16]	Controlled burn, National Pinelands Reserve NJ, pitch pine and scrub oak understory	Water trays, some with plastic film	80% less than 2 cm^2
Filkov et al. [17]	Controlled burn, National Pinelands Reserve NJ, pitch pine and scrub oak understory	Water trays, some with plastic film	80% between 0.5-2 cm^2
Thomas et al. [18]	Controlled burn, National Pinelands Reserve NJ, pitch pine and scrub oak understory	Water trays	80% between 0.075-0.5 cm^2
Rissel et al. [19]	2011 Bastrop Complex Fire, loblolly pine with yaupon understory	Trampolines	90% less than 0.5 cm^2
Kapcak [33]	Canadian Boreal Community FireSmart Project, no vegetation information	Water trays, fire retardant sheets	90% of scorch marks less than 0.1 cm^2

Table A.3: Tree measurements

Test	Tree	Species[a]	Moisture content	Initial mass [kg][b]	Mass loss [kg][b]	Height [m]	DBH [mm]
1	1	DF	17%	4.33	0.99	3.73	36
2	1	DF	15%	8.51	3.71	3.71	53
3	1	DF	20%	9.83	2.89	4.72	61
4	1	GF	36%	7.47	3.68	4.50	49
5	1	GF	75%	8.42	2.89	3.56	65
6	1	GF	24%	3.39	1.29	3.94	40
6	2	GF	19%	7.63	3.94	3.61	44
6	3	GF	35%	4.53	2.12	3.78	36
7	1	DF	27%	5.93	2.67	3.99	49
7	2	DF	25%	5.67	2.19	4.62	44
7	3	DF	18%	5.28	2.79	3.71	36
9	1	GF	40%	4.00	1.78	4.29	44
9	2	GF	17%	7.85	2.57	4.32	61
9	3	GF	25%	5.91	2.63	3.61	44
9	4	GF	41%	5.40	2.49	4.06	53
9	5	GF	13%	4.11	1.46	3.73	36
10	1	DF	37%	4.21	1.17	4.60	49
10	2	DF	19%	4.25	1.94	3.61	32
10	3	DF	20%	2.53	0.79	3.94	32
10	4	DF	18%	3.18	1.23	3.78	32
10	5	DF	20%	3.13	0.67	4.04	36
11	1	DF	15%	4.64	1.69	3.86	44
11	2	DF	13%	7.73	3.93	2.95	44
11	3	DF	18%	6.42	2.81	3.40	40
11	4	DF	24%	5.59	3.09	2.97	40
11	5	DF	15%	3.71	1.35	3.30	40
12	1	GF	19%	7.61	3.66	4.47	49
12	2	GF	15%	4.29	2.17	3.73	36
12	3	GF	13%	8.21	4.86	3.63	44
13	1	DF	16%	3.71	1.64	3.91	32
13	2	DF	13%	7.56	4.60	4.17	49
13	3	DF	13%	2.74	0.53	3.10	28
14	1	GF	11%	15.83	6.75	4.09	73
15	1	GF	26%	9.43	6.10	4.29	49
15	2	GF	17%	11.21	6.93	4.47	57
15	3	GF	48%	4.32	2.43	3.58	40
15	4	GF	38%	5.04	2.76	4.27	49
15	5	GF	49%	5.54	2.05	4.04	57
16	1	DF	22%	5.67	2.96	3.23	44
16	2	DF	15%	4.39	2.92	3.78	36
16	3	DF	24%	5.58	2.59	3.68	36
16	4	DF	59%	5.11	2.26	4.11	49
16	5	DF	23%	5.15	1.74	4.67	44

Test	Tree	Species[a]	Moisture content	Initial mass [kg][b]	Mass loss [kg][b]	Height [m]	DBH [mm]
17	1	GF	21%	16.08	8.35	3.96	57
17	2	GF	31%	7.06	4.69	3.76	44
17	3	GF	21%	4.91	3.05	4.37	40
17	4	GF	54%	5.18	2.91	4.57	49
17	5	GF	14%	3.29	1.10	3.18	36
18	1	DF	21%	8.58	3.23	4.45	49
18	2	DF	23%	6.00	3.12	4.17	44
18	3	DF	18%	8.68	4.28	4.32	53
19	1	GF	15%	15.89	9.39	4.42	65
19	2	GF	21%	4.82	1.44	3.73	44
19	3	GF	39%	3.66	1.44	3.61	44
20	1	WJ	45%	19.95	3.07	4.45	77
21	1	WJ	54%	11.33	4.86	4.19	73
21	2	WJ	115%	3.47	2.00	2.95	44
21	3	WJ	36%	6.40	2.90	2.77	32
22	1	PP	146%	9.28	2.77	3.91	81
22	2	PP	57%	10.33	1.33	3.56	69
22	3	PP	25%	16.29	1.72	3.66	77
23	1	WJ	37%	12.09	7.38	2.84	49
23	2	WJ	57%	5.90	3.00	3.35	36
23	3	WJ	51%	5.59	2.95	3.05	44
23	4	WJ	28%	4.36	1.91	2.74	32
23	5	WJ	42%	5.92	1.20	3.53	49
24	1	PP	75%	11.97	2.84	3.76	73
24	2	PP	97%	6.97	1.72	3.68	69
24	3	PP	92%	5.36	1.74	3.71	57
24	4	PP	60%	7.14	0.91	3.71	65
24	5	PP	90%	5.03	1.08	3.63	57
25	1	PP	155%	8.22	1.21	3.38	69
25	2	PP	193%	4.40	0.60	3.99	69
25	3	PP	129%	5.59	0.44	3.71	65
26	1	PP	37%	14.56	3.11	3.94	77
27	1	WJ	39%	19.33	9.59	3.81	73
27	2	WJ	35%	10.51	5.83	2.64	40
27	3	WJ	28%	7.95	4.31	2.92	44
27	4	WJ	32%	4.17	2.08	2.82	40
27	5	WJ	65%	5.05	2.51	2.29	40
28	1	WJ	42%	15.00	6.73	3.89	73
29	1	PP	66%	13.56	1.93	3.84	77
30	1	WJ	25%	17.44	9.30	3.35	44
30	2	WJ	13%	9.03	4.60	2.79	49
30	3	WJ	63%	4.20	2.42	2.29	36
31	1	PP	109%	9.41	1.41	3.71	81
32	1	WJ	31%	22.23	10.41	4.22	93
32	2	WJ	23%	7.65	3.86	2.82	49

Test	Tree	Species[a]	Moisture content	Initial mass [kg][b]	Mass loss [kg][b]	Height [m]	DBH [mm]
32	3	WJ	22%	11.12	6.77	2.44	32
33	1	WJ	34%	16.83	7.54	2.90	61
33	2	WJ	33%	10.03	5.24	3.66	53
33	3	WJ	37%	10.97	5.67	3.30	49
33	4	WJ	34%	3.57	2.12	2.11	32
33	5	WJ	31%	5.77	3.67	2.18[c]	32[c]
34	1	PP	85%	9.57	2.27	3.84	65
34	2	PP	186%	6.04	0.25	3.76	77
34	3	PP	172%	6.17	1.09	3.78	77
34	4	PP	153%	2.61	0.59	3.71	49
34	5	PP	35%	3.85	0.67	2.90	40
35	1	PP	66%	9.35	1.53	3.91	65
35	2	PP	87%	9.10	0.59	3.73	65
35	3	PP	52%	11.27	2.14	3.66	73
35	4	PP	92%	6.68	0.37	3.78	65
35	5	PP	75%	7.49	0.66	3.71	57
37	1	WJ	28%	18.48	6.28	4.50	69
38	1	PP	52%	8.40	0.33	3.68	65
38	2	PP	156%	5.33	1.13	3.71	65
38	3	PP	80%	9.15	0.53	4.17	73

[a] DF = Douglas-fir, GF = grand fir, WJ = western juniper, PP = ponderoa pine

[b] Corrected for moisture content. See Section 3.2.2 for details.

[c] Values estimated based on neighboring trees. Actual measurements unavailable.

Table A.4: Data used for ember and char mark regression models. Moisture content and ember aspect ratio values are average value per test.

Number of trees	**Moisture content**	**Mass loss [kg]**	**Species**[a]	**Ember aspect ratio**	**Ember counts**	**Char counts**
1	17%	0.99	DF	17.26	403	82
1	15%	3.71	DF	10.58	126	38
1	20%	2.89	DF	23.23	758	46
1	36%	3.68	GF	11.93	85	19
1	75%	2.89	GF	8.89	1340	465
3	26%	7.35	GF	11.72	266	125
3	24%	7.65	DF	19.41	1380	283
5	27%	10.90	GF	9.52	328	73
5	23%	5.79	DF	18.42	208	20
5	17%	12.90	DF	11.49	90	11
3	16%	10.70	GF	6.13	1030	476
3	14%	6.77	DF	20.67	328	80
1	11%	6.75	GF	8.14	1260	654
5	36%	20.30	GF	8.82	140	62
5	29%	12.50	DF	14.16	346	131
5	28%	20.10	GF	16.08	9	1
3	21%	10.60	DF	16.11	499	78
3	25%	12.30	GF	8.58	430	219
1	45%	3.07	WJ	5.87	424	110
3	68%	9.76	WJ	5.33	574	465
3	76%	5.82	PP	37.73	343	54
5	43%	16.40	WJ	6.33	615	499
5	83%	8.29	PP	33.76	319	29
3	159%	2.25	PP	42.81	123	8
1	37%	3.11	PP	34.95	384	2
5	40%	24.30	WJ	6.04	501	404
1	42%	6.73	WJ	5.99	216	190
1	66%	1.93	PP	30.95	195	18
3	34%	16.30	WJ	6.00	735	514
1	109%	1.41	PP	24.56	39	1
3	25%	21.00	WJ	6.27	53	23
5	34%	24.20	WJ	5.91	1140	426
5	126%	4.87	PP	30.84	236	26
5	74%	5.29	PP	44.18	208	28
1	28%	6.28	WJ	4.95	522	231
3	96%	1.99	PP	43.23	58	16

[a] DF = Douglas-fir, GF = grand fir, WJ = western juniper, PP = ponderoa pine

Appendix B: Figures

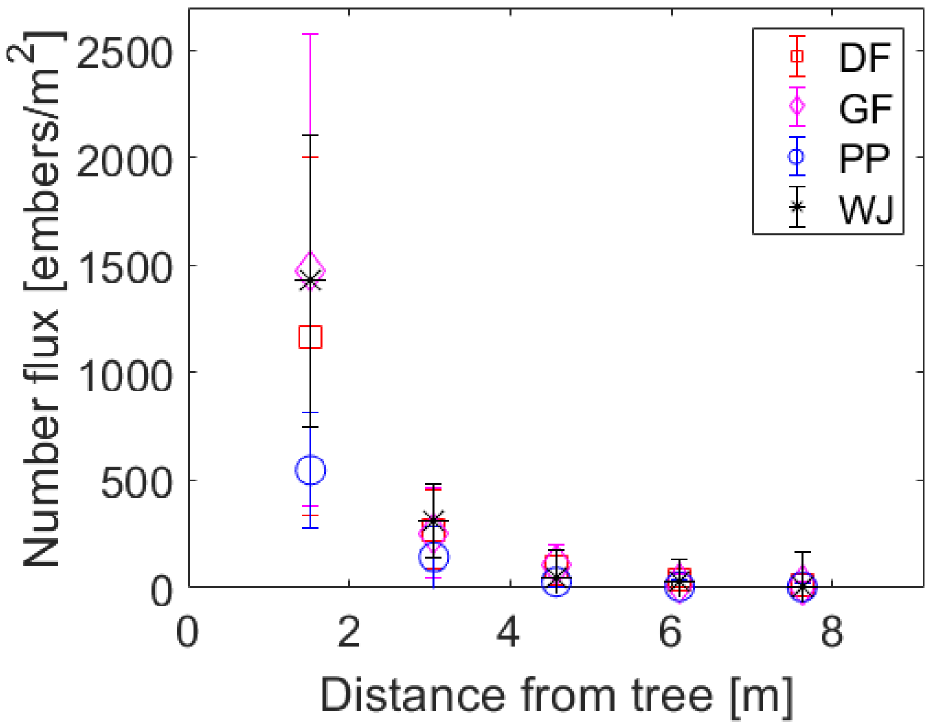

Figure B.1: Average ember flux per test with precision uncertainty

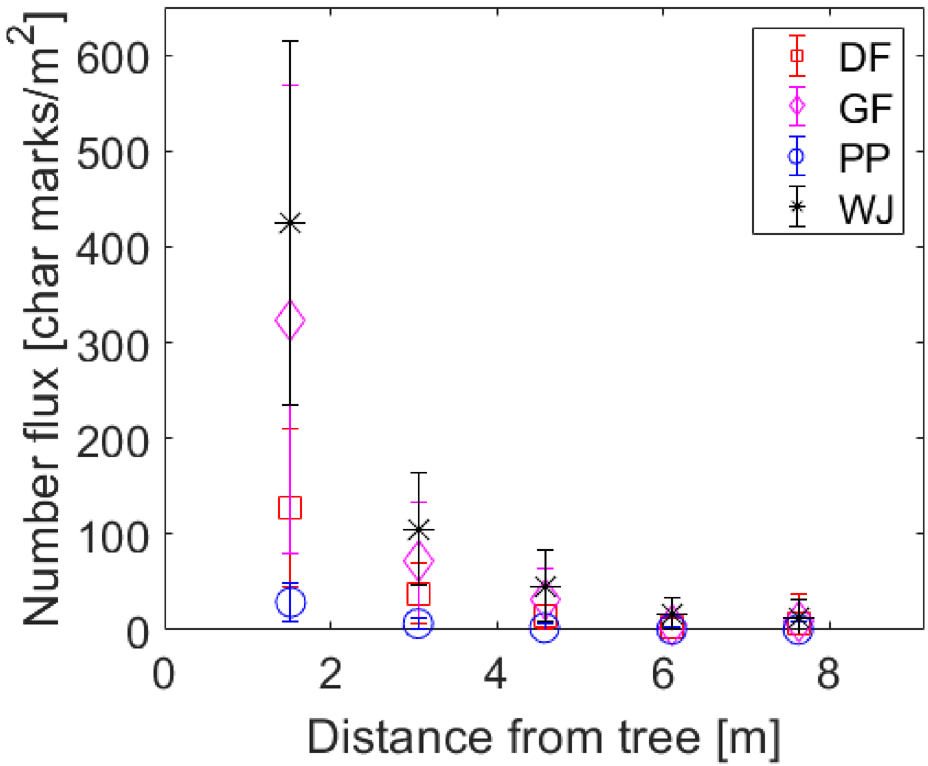

Figure B.2: Average char mark flux per test with precision uncertainty