

## AN ABSTRACT OF THE THESIS OF

Hamid Fazeli for the degree of Master of Science in Mechanical Engineering  
presented on June 3, 2022.

Title: Identification of Physical and Chemical Processes on Ignition and  
Burning of Live Fuels

Abstract approved:

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David L. Blunck

Wildland fire refers to an unpredictable and uncontrollable fire that happens in wildland areas. Regardless of the beneficial impacts of wildland fires on ecosystems, the destructive impacts of wildfires on air quality, economy, public health, etc. are considerable. An essential goal in the fire community is that the wildland fires get controlled and managed when they may have destructive impacts. To achieve this goal, in the first step, it is necessary to study the ignition and burning behavior of live fuels. Many fires burn live and a combination of live and dead fuels. Therefore, more parameters are involved in the ignition and burning of live fuels than those in dead fuels. Ignition and burning of live fuel are still potential subjects for further research due to a lack of knowledge regarding its behavior. This study will seek to identify the physical and chemical processes in live fuel ignition and burning. Hence, this work is comprised of two studies focused on identifying key physical and chemical processes in the ignition and burning of live fuels.

In the first study, the ignition and burning behaviors of live fuels in different convective heat fluxes were evaluated. The species evaluated consist of different species such as longleaf pine (*Pinus palustris*), Douglas-fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), ponderosa pine

(*Pinus ponderosa*), western larch (*Larix occidentalis*), pacific yew (*Taxus brevifolia*), white spruce (*Picea glauca*), and sagebrush (*Artemisia tridentata*). The ignition and burning behaviors were related to live fuel moisture content (LFMC), pilot flame temperatures, and convective heat fluxes. Individual needles were suspended above a flat flame burner, and the resulting ignition process was recorded using a high-speed camera. In general, four burning stages can be observed: droplet burning, transition, flaming, and smoldering combustion. Ejection and subsequent burning of droplets can occur prior to sustained flaming ignition only in live fuels. For some species (e.g., longleaf pine, ponderosa pine, white spruce), droplet ejection and burning can reduce ignition times relative to dried fuel with lower LFMC. In general, the transition stage tends to take longer than the flaming and droplet stages (when these occur). During the transition stage, the fuels are heated, and pyrolysis occurs. Time-scales to ignition and the different stages of ignition and burning vary more among live fuels than dead and dried fuels. This conclusion indicates that other parameters, such as chemical composition and structural morphology of the fuel, can significantly influence the burning of live fuels.

In the second study, the influence of chemical composition and seasonal variability on the ignition and burning of four living conifer species were investigated. The species studied include long-leaf pine (*Pinus palustris*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*). Individual needles were held 2 cm above a flat flame burner, and the resulting ignition and burning processes were recorded using a high-speed camera to identify the time of droplet, transition, and flaming/smoldering stages for each species. After finding the time of each stage, then the samples were put on the burner for a specific time to collect enough droplet, transition, and flaming/smoldering samples for chemistry

analysis. Live fuel moisture content (LFMC), chemical composition, and time-to-ignition of live fuels at the constant heating condition are reported. Finally, the variation of chemical composition, live fuel moisture content, time-to-ignition, and the time-scale of live fuel burning are measured to evaluate the impact of seasonal variability.

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Identification of Physical and Chemical Processes on Ignition and Burning of  
Live Fuels

by  
Hamid Fazeli

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Hamid Fazeli, Author

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## Chapter 1: Introduction

### 1.1 Motivation

Regardless of the beneficial impacts of wildland fires on ecosystems, recent years have seen an increase in damages due to wildland fires throughout the world (Weise & Wotton, 2010). As noted in a report from Northwest Interagency Coordination Center, over 1.98 million acres were burned in 2020 by fire in northwestern states, more than 223% of the ten-year average. This caused 130 to 150 billion dollars in damage to forests and residential areas (Northwest Interagency Coordination Center Report, 2020). In short, better prediction and management of wildland fires are critical to decreasing the destructive impacts of wildfires on air quality, economy, public health, etc. (Johnson & Miyanishi, 2001). Wildland fire research can help the fire community to develop the next generation of fire models to better predict the spread of fires (Sullivan, 2009). Much learning is still needed, however, to identify what parameters play important roles in the ignitability and flammability of live fuels (Finney et al., 2012; Jolly & Butler, 2015).

### 1.2 Overview

This work seeks to achieve a better understanding of key physical and chemical processes of live fuel ignition and combustion. This work consists of two studies including physical and chemical ignition and burning processes. Physical processes such as droplet burning, and eruptive jetting are still

relatively unknown phenomena and their contribution to the ignition and burning of live fuel needs more investigation. In addition, understanding the impact of different convective heat fluxes on the ignition and burning behavior of live and dead fuels is still unclear. Some species do not show droplet and/or flaming stage(s) in their ignition and burning processes. Furthermore, we need to answer why species of different chemical compounds behave differently during ignition and burning.

In both studies (i.e., physical and chemical studies), individual needles or leaves were suspended above a flat flame burner (i.e., McKenna), and the resulting ignition process was recorded using a high-speed camera. In addition, an MKS flow controller (model 247D) was used to adjust the volumetric flow rate of hydrogen and air for the burner. The MKS was calibrated using an Alicat mass flowmeter (model M250SLPM-D/5M). A K-type thermocouple was used to measure the foliage surface temperatures. A Phantom V711 high-speed camera was used to capture images of the ignition process. In the foliage chemistry analysis, two extractors (model Ankom XT4 and XT15) were used to extract crude fat.

This project was completed in collaboration with Oregon State University (OSU) and USDA Forest Service and supported financially by Strategic Environmental Research and Development Program (SERDP). Analysis of the ignition and burning behavior of eight species of live and dead species in both studies was performed in Combustion, Ignition, Radiation, and Energy Laboratory (CIRE Lab) at Oregon State University. The foliage chemistry analysis of four species was conducted in Missoula Fire Sciences Laboratory at USDA Forest Service.

### 1.3 Objectives

The research seeks to identify key physical and chemical processes in the ignition and burning behavior of live fuels. The objectives of this study are as follows. First, to identify and quantify the time-scales associated with the various stages leading up to and including the burning of live fuels. Second, to determine how the stages of ignition and burning change with drying of fuels for different species. Third, to better understand how moisture content impacts the burning of live and dead fuels. Fourth, to learn how the ignition sensitivities of dead and live fuels are affected by changing the heat fluxes. Fifth, to compare how different species of vegetation ignite and burn. Sixth, to identify and quantify chemical components of foliage chemistry in live fuels by chemistry analysis. Seventh, to determine how the stages of ignition and burning change with crude fat and LFMC. Eighth, to better understand how seasonally changing crude fat concentration impacts the ignition of live fuels. Ninth, to learn how the ignition of live fuels is affected by changes in moisture content month by month.

### 1.4 Outlines of Thesis

The outline of this thesis is as follows: Chapter 2 discusses the stages and time-scales of ignition and burning of live fuels for different convective heat fluxes are reported. Chapter 2 is a manuscript that has been published in the Fuel journal. Chapter 3 reports the influence of foliage chemistry and seasonal variability on the ignition and burning of live fuels. Similarly, Chapter 3 is a manuscript; it is being prepared for submission for peer review. Finally, a summary of conclusions and future works of the project are explained in Chapter 4.

# Stages and Time-Scales of Ignition and Burning of Live Fuels for Different Convective Heat Fluxes

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## Chapter 2: Stages and Time-Scales of Ignition and Burning of Live Fuels for Different Convective Heat Fluxes

### Abstract

Wildland fires impact ecosystems and communities worldwide. Many wildfires burn in living or a mixture of living and senescent vegetation. Therefore, it is necessary to understand the burning behavior of living fuels, in contrast to just dead or dried fuels, to more effectively support fire management decisions. In this study, the ignition and burning behaviors of needles placed in convective heat flux were evaluated. The species included longleaf pine (*Pinus palustris*), Douglas-fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), pacific yew (*Taxus brevifolia*), white spruce (*Picea glauca*), and sagebrush (*Artemisia tridentata*). The ignition and burning behaviors were related to live fuel moisture content (LFMC), pilot flame temperatures, and convective heat fluxes. The different stages of ignition and burning were captured using high-speed imaging. In general, four burning stages can be observed: droplet ejection and burning, a transition stage, flaming combustion, and smoldering combustion. Ejection and subsequent burning of droplets can occur prior to sustained flaming ignition only in live fuels. For some species (e.g., longleaf pine, ponderosa pine, white spruce), droplet ejection and burning can reduce

ignition times relative to dried fuel with lower LFMC. In general, the transition stage tends to take longer than the flaming and droplet stages (when these occur). During the transition stage, the fuels are heated, and pyrolysis occurs. Time-scales to ignition and the different stages of ignition and burning vary more among live fuels than dead and dried fuels. This conclusion indicates that other parameters, such as chemical composition and structural morphology of the fuel, can significantly influence the burning of live fuels.

Keywords: *live fuel, foliage fuel, moisture content, droplet burning, high-speed imaging*

## 2.1 Introduction

Better prediction and management of wildland fires are essential goals for reducing their destructive impacts. Wildland fire models can be valuable tools to predict fire spreads (Weise & Wotton, 2010). One explicit limitation of many fire models is that they treat live fuels (i.e., live) as dead fuels that are wet (Fons, 1946; Fosberg & Schroeder, 1971; Rothermel, 1972; Countryman 1974; Grishin & Perminov, 1998; Porterie et al. 2003). This assumption is problematic because the storage of moisture differs between live and dead fuels. Equally important, the chemical compositions of live, dead, and dried fuels can be different (Weise & Wotton, 2010). Unfortunately, limitations in the fire community's understanding of ignition and fire spread among live fuels have contributed to inaccurate models of wildfire propagation (Sullivan, 2009). Hence, a key to enabling more accurate modeling of the burning of live fuels is a better understanding of the physics associated with ignition and fire spread among live fuels (Finney et al., 2012; Jolly & Butler, 2015).

Live fuel moisture content (LFMC) plays an influential role in the ignition and burning behavior of fuels (Susott, 1980; Xanthopoulos & Wakimoto, 1993; Johnson & Miyanishi, 2001; Dimitrakopoulos & Papaioannou, 2001; Pickett et al. 2005; Fletcher et al., 2007; Pickett et al., 2010; Jervis, 2010; Cohen & Finney, 2010; Anand et al., 2017; Borujerdi et al. 2020; Ramadhan, 2021; Fazeli et al. 2021). As a result, many studies have investigated the influence of LFMC on the flammability of fuels. As expected, increasing the moisture content and thickness of foliage increases the ignition time of live fuels (Pickett et al. 2005; Fletcher et al., 2007; Pickett et al., 2010; Ramadhan, 2021; Jervis, 2010). Moisture evaporating from fuels can impact burning by diluting flammable pyrolyzates (i.e., gas around the live fuel), absorbing thermal energy, possibly altering combustion reactions, and ultimately delaying the time to

ignition in dead and live fuels (Johnson & Miyanishi, 2001; Pickett et al. 2005; Fletcher et al., 2007; Pickett et al., 2010; Ramadhan, 2021; Jervis, 2010; Fazeli et al. 2021). In some instances, live fuels have displayed blistering on the surface of the fuel, droplet ejection, or bursting of the structure while burning (Pickett et al. 2005; Ramadhan, 2021; Jervis, 2010; Fazeli et al. 2021). Note, however, that changes in ignition phenomena caused by differences in species composition, moisture content, or environmental conditions have not been established.

Moisture storage differs between dead and live fuels. Dead fuels store moisture inside the fiber structure of the foliage as an inter-structure liquid and vapor. In live fuels, most of the water is stored in the xylem, and the remaining moisture is stored in cells. During the heating of live fuels, liquids, including water and extractives, begin to evaporate inside the cells. Eventually, the gases exit from the foliage and are released (Johnson & Miyanishi, 2001; Zhang et al., 2020). Released gases can differ depending on the heat flux and foliage cellular structures (Johnson & Miyanishi, 2001). The first form of gas release is caused by rupturing of the cell walls as the pressure increases within. The gas is consequently released through tiny pores on the foliage. The second form of gas releasing can be observed as an “eruptive jetting” or “micro-explosion,” often with an audible phenomenon. In some species, eruptive jetting impacts the burning of live fuel and increases its flammability (Zhang et al., 2020; Ahmad et al., 2021).

Previous studies have investigated the relationship between LFMC, ignition, and burning of live fuels. However, LFMC might not be the only parameter for predicting the occurrence of some fires (Pickett et al. 2005; Fletcher et al., 2007; Alexander & Cruz, 2013). Other parameters that affect the burning of live fuel, such as foliar (leaf) chemistry (Brown et al., 2003;

Alessio et al., 2008; Ormeño et al., 2009; Guo et al. 2010; Jolly et al. 2010) or heat flux rates (Engstrom et al. 2004; Migliorini et al., 2008; McAllister et al., 2012; McAllister & Finney, 2014; Fares et al. 2017), should be investigated (Jolly & Butler, 2015; Finney et al., 2012). Of note to this work, two modes of heat transfer are dominant in the spread of wildfires. Radiation heat transfer serves as a pre-heating process to increase the surface temperature of live fuels, while convection further increases their temperature (Jolly et al. 2010; McAllister et al. 2012). A wide range of heat fluxes can occur in wildland fires (Engstrom et al., 2004). As a result, the ignition sensitivity of dead and live fuel exposed to various heat fluxes is a key parameter that must be considered when predicting the ignition and burning of live fuels.

With this motivation and background, the overall goal of this work is to better understand the ignition process of live fuels. This goal is accomplished through addressing five specific objectives of this work. First, to identify and quantify the time-scales associated with the various stages leading up to and including the burning of live fuels. Second, to determine how the stages of ignition and burning change with drying of fuels for different species. Third, to better understand how moisture content impacts the burning of live and dead fuels. Fourth, to learn how the ignition sensitivities of dead and live fuels are affected by changing the heat fluxes. Fifth, to compare how different species of vegetation ignite and burn. It is expected that knowledge gained in this study can be used by the fire community to better understand the ignition and burning of live fuels and can be used to improve physics-based fire behavior models.

## 2.2 Experimental approach

### 2.2.1 Experimental arrangement

Individual needles were suspended above a flat flame burner, and the resulting ignition process was recorded using a high-speed camera during the experiments. Figure 2.1 shows the arrangement, which consisted of flow controllers, a flat flame burner (FFB), a high-speed camera, and a cooling pump. The flat flame burner (i.e., McKenna) consists of a porous plug 6 cm in diameter (Migliorini et al., 2008). Furthermore, FFB has the lowest thermal radiation due to the use of a cooling circuit, which is therefore very suitable for studying the convective heat effects. The burner was operated with a mixture of hydrogen/air at an equivalence ratio ( $\Phi$ ) of 1.24. This  $\Phi$  allowed the desired temperatures (and convective fluxes) to be obtained in a fuel-rich environment. A fuel-rich environment is expected for many conditions where flames are near vegetation. The MKS flow controller (model 247D) was used to adjust the volumetric flow rate of hydrogen and air for the burner. The MKS was calibrated using the Alicat mass flowmeter (model M250SLPM-D/5M).

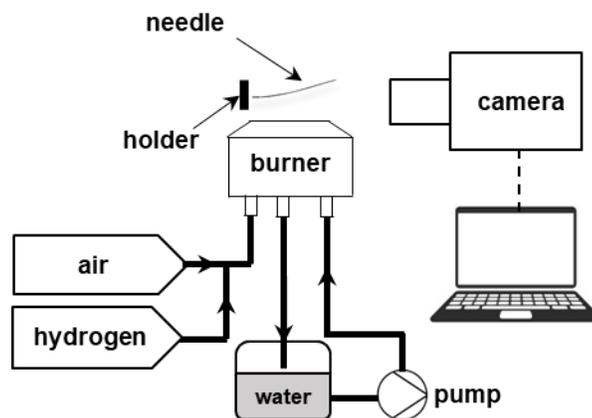


Figure 2.1: Experimental arrangement for studying ignition and burning of species for various convective fluxes.

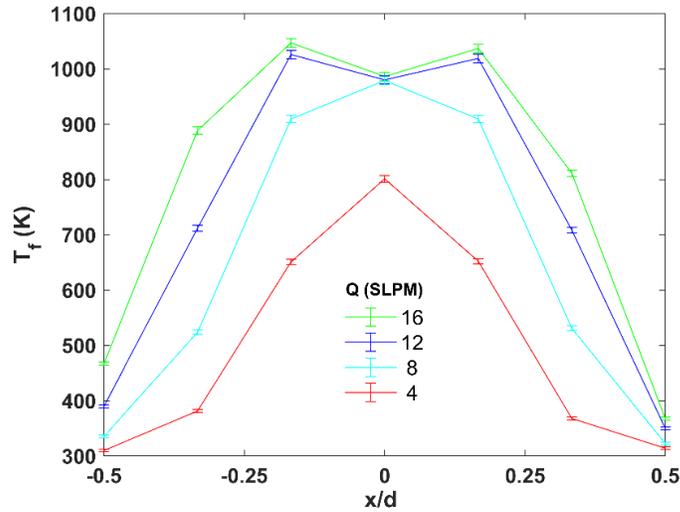


Figure 2.2: The distribution of the flame temperature ( $T_f$ ) above the burner for different heating cases. The overall equivalence ratio ( $\Phi$ ) was 1.24.

The tests were conducted with the individual needle held 2 cm above the burner surface. Figure 2.2 shows the flame temperature ( $T_f$ ) distribution across the burner at this height for different flow rates or reactants. A type-K thermocouple was used to collect the measurements. Changes in flow rates allowed the convective fluxes to be varied.

The mean flame temperature ( $T_m$ ), which was used to estimate convective fluxes to the foliage, was estimated based on the average of the temperatures at the location where the samples were positioned. The  $T_m$  that was studied were 1025, 1010, 930, and 700 K.

A Phantom V711 high-speed camera was used to capture images of the ignition process at a frequency of 1000 frames per second (fps) and an exposure time of 400 ( $\mu$ s). High-speed images were analyzed to identify different processes and their time-scales leading up to ignition. The camera software was used while analyzing images.

### 2.2.2 Fuel collection and analysis

Ignition and burning behavior of seven species of conifer trees and one shrub were evaluated during tests, as listed in Table A.1. The specific species considered included longleaf pine (*Pinus palustris*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), western red cedar (*Thuja plicata*), white spruce (*Picea glauca*), pacific yew (*Taxus brevifolia*), and sagebrush (*Artemisia tridentate*). These species were considered because of their significance to wildfires, their availability for harvesting, and their contrast in chemical composition. All coniferous species were harvested in the regions near Corvallis, Oregon (44.5638° N, 123.2794° W), and sagebrush was harvested near Bend, Oregon (44.0429° N, 121.3334° W) in the United States of America. Species were harvested and burned from September to February. The live fuel samples were kept in a plastic bag to prevent water and volatile loss.

Three types of samples were tested: live fuels, live fuels that were allowed to dry (referred to as dried fuel), and dead fuels. The live fuels were collected and burned within a day of being harvested, with the exception of sagebrush, which was burned within a week after harvesting. Typical moisture contents were 120-155%. Dried fuels were dried in the air for 30 days to achieve moisture contents in the range of 5-120%. Dead fuels were fallen leaves/needles collected near the selected shrub/trees and dried to reach a moisture content close to 0. It is noted that the samples were typically collected from the same trees. As such, the chemical composition of the samples for a species of shrub/tree is expected to be similar between tests other than seasonable variability.

The oven-drying method was used to determine the LFMC (Jolly & Hadlow, 2011). The samples were placed in an oven at 103°C for four days to

dry. The percentage of LFMC as per the dry weight of the sample was calculated using the relationship,

$$\text{LFMC}(\%) = \frac{\text{weight of the liquid in a sample}}{\text{dry weight of a sample}} = \frac{w_{\text{wet}} - w_{\text{dry}}}{w_{\text{dry}} - w_{\text{cont}}} \times 100\% \quad (2.1)$$

where  $w_{\text{wet}}$  is a wet sample,  $w_{\text{dry}}$  is the weight of a dry sample, and  $w_{\text{cont}}$  is the weight of the container.

### 2.2.3 Estimation of convective heat flux

The convective heat flux to the needle/leaf,

$$q_{\text{conv}} = h (T_{\text{m}} - T_{\text{s}}), \quad (2.2)$$

was estimated for the different flow conditions and needle geometries. Here  $h$  is the convective heat coefficient,  $T_{\text{m}}$  is the mean flame temperature, and  $T_{\text{s}}$  is the initial temperature of the fuel prior to insertion (i.e., 20°C). It is noted that this estimation of  $q_{\text{conv}}$ , is for the initial conditions, and will decrease as the foliage is heated. The initial heat flux is expected to be the best metric for comparing the relative heating conditions among the needles.

Nusselt number ( $Nu$ ) correlations for a cylinder or a flat plate were used to estimate convective heat coefficient ( $h$ ), depending on the geometry of the needle. The correlation for a cylinder in a cross-flow (Churchill & Bernstein, 1977),

$$Nu_{\text{D}} = \frac{hD}{k} = 0.3 + \frac{0.62Re_{\text{D}}^{1/2}Pr^{1/3}}{[1+(0.4/Pr)^{2/3}]^{1/4}} \left[ 1 + \left( \frac{Re_{\text{D}}}{282000} \right)^{5/8} \right]^{4/5} \quad PrRe_{\text{D}} > 0.2, \quad (2.3)$$

was used to characterize convective heat transfer for the needle-type species, including longleaf pine, Douglas-fir, ponderosa pine, western red cedar, white spruce, western larch.  $k$  is the thermal conductivity of air,  $D$  is the characteristic diameter of the needle,  $Pr$  is the Prandtl number of the air, and  $Re_{\text{D}}$  is the

Reynolds number of gas flow around the needle. The width of a needle was assumed as  $D$ . The shapes of the needles are not truly cylindrical, but this geometry seemed most representative for heat transfer correlations.

The correlation for a flat plate was determined by Hilpert & Reiher (2004):

$$Nu_L = \frac{hL}{k} = 0.231 Re_L^{0.731} \quad (2.4)$$

was used to estimate convective fluxes through leaves of pacific yew and sagebrush. Here  $L$  is the projected width of the flat plate (i.e., leaf) perpendicular to the freestream. The  $Re$  of the flow was less than that evaluated for the correlation ( $6.3 \times 10^3$  to  $2.36 \times 10^4$ ). However, no other suitable correlation valid for the  $Re$  of this study (i.e., between 0.3 to 18.8) was found. Thus, the relationship (2.4) was used to approximate the Nusselt number for flow around the aforementioned species. The ranges of convective heat fluxes evaluated were between 5 to 95 (kW/m<sup>2</sup>), as reported in Table A.2. In order to validate the estimated heat fluxes, the range of heat flux compared to other works (Engstrom et al. 2004; McAllister et al. 2012) are within the acceptable range between 5-100 kW/m<sup>2</sup>. Four different heat fluxes are estimated for the four different gas temperatures above the burner, as listed in Table A.2 for each species.

## 2.3 Results and Discussion

### 2.3.1 Multi-stage of burning observed in live fuels

Ignition and burning of the samples can occur across several stages, as identified from the high-speed images. The occurrence and duration of these stages vary depending on the species, heat flux, and moisture content. The stages can

include droplet ejection/burning, transition, flaming, and smoldering combustion. The characteristics of each stage are now briefly described and discussed.

### 2.3.1.1 First stage: Droplet burning

Droplets form on the surface of the foliage as samples are inserted into the flame, and, in some instances, the droplets are ejected from the surface. As will be discussed shortly, the evidence shows that ejected droplets burn, particularly after leaving the surface. Fig. 2.3a shows an example of droplets on the needle surface and all three panels of Fig. 2.3 show droplets that have ejected and are burning. The size of the droplets in the air in Fig. 2.3.b is estimated to be much less than 0.5 mm. Flames can be observed during the droplet burning stage, as shown in the color image of Fig. 2.3.c. It is presumed that the surface droplets burn, but this is difficult to verify. It is noted that these droplets are not always observed, depending on the heat flux, species composition, and moisture content of the fuel. Physically, droplets leave the foliage as the heating causes the intercellular liquid to heat, partially vaporize, and leave the plant. The liquid consists of a mixture of water and extractives (Jolly et al. 2010). Openings in

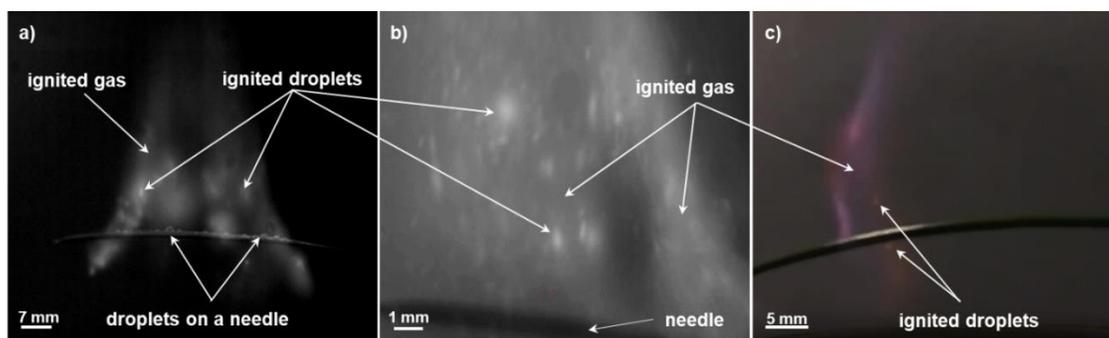


Figure 2.3: High-speed and color images of droplet burning in (a) longleaf pine (b) Douglas-fir (c) ponderosa pine.

the epidermis of the needles (via stomata) allow droplets and vapor release (Johnson & Miyanishi, 2001), although presumably, the epidermis may rupture in some conditions and provide a second avenue for moisture release.

A mist of saturated water-sugar solution and water was sprayed above the burner to evaluate whether the droplets observed were actually burning or simply reflecting light. The water-sugar solution was a simple surrogate for fluids ejected from foliage. A pressure atomizer was used to inject spray into the flame. Representative images from the experiments with a saturated water-sugar solution and pure water are shown in Fig. 2.4. The droplets ( $< 1$  mm in diameter) with saturated water-sugar solution are visible (see Fig. 2.4a), similar to the droplets observed in Fig. 2.3. In contrast, no droplets were visible with just water (see Fig. 2.4b). The results from this experiment are evidence that the droplets observed above the needles are burning and not just visible because of reflected light. The significance of droplet ejection is that this process distributes both fuel and moisture away from the foliage. As a result, the overall burning time can be decreased under some conditions, as discussed in Section 3.3.

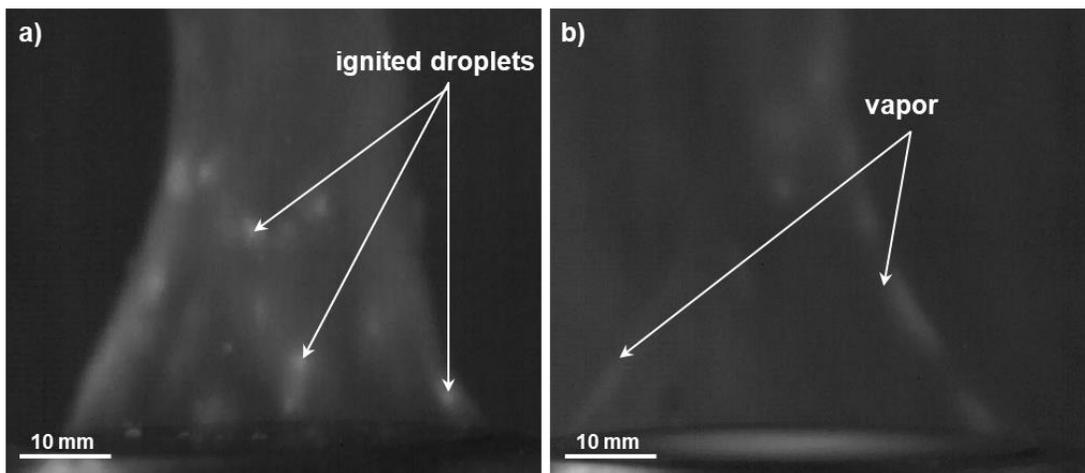


Figure 2.4: High-speed images of droplet burning of (a) saturated water-sugar solution (b) vapor of pure water.

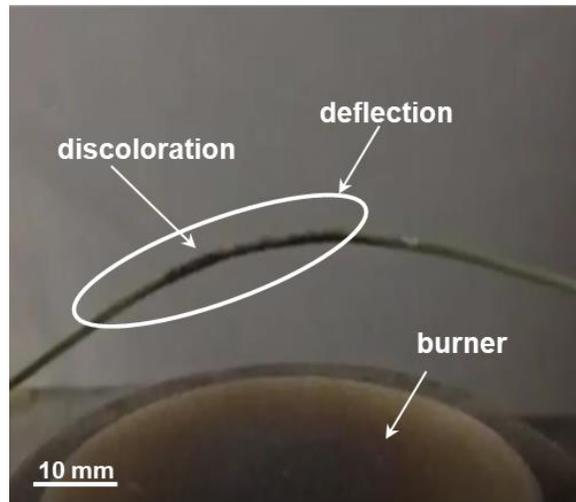


Figure 2.5: The transition stage with discoloration and deflection in the ponderosa pine needle.

### 2.3.1.2 Second Stage: Transition

The visible discoloration shown in Fig. 2.5 is evidence of pyrolysis during the transition stage. Long-chain carbon molecules such as lignin, cellulose, and hemicellulose are converted into pyrolyzates (Dietenberger et al., 2018). Ignition indicates the end of the transition stage. In some experiments, eruptive jetting occurred during transition and/or droplet burning stages. Eruptive jetting refers to the rapid ejection/burning of the gases from a needle/leaf to the surroundings (Engstrom et al., 2004; McAllister et al., 2014). An example of this process is shown in Fig. 2.6. Eruptive jetting is not considered a separate stage in this

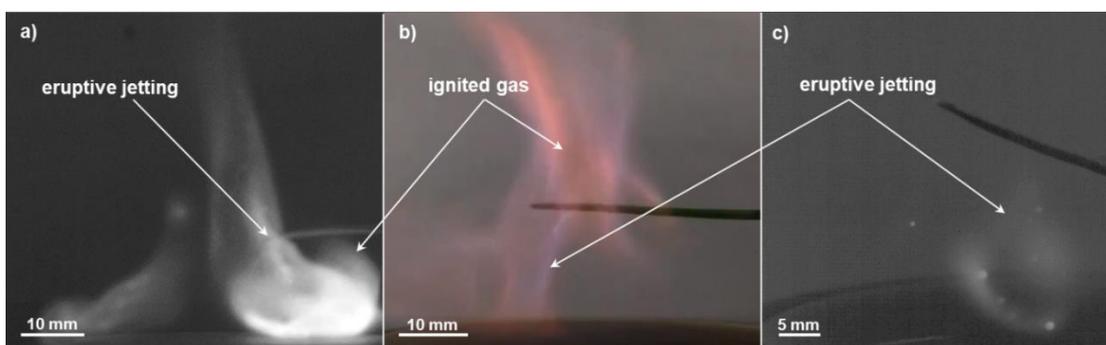


Figure 2.6: High-speed and color images of micro-explosion (eruptive jetting) in (a) Douglas-fir (b) western larch (c) Pacific yew.

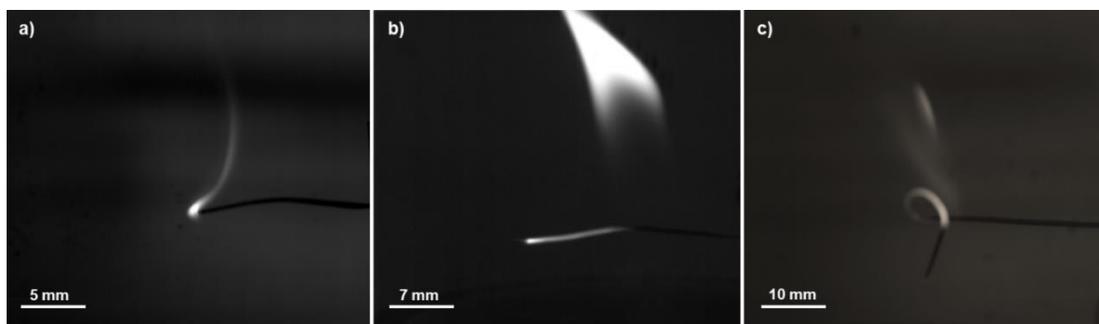


Figure 2.7: The flaming combustion process in different coniferous species; (a) ignition in Douglas-fir, (b) flaming in western larch, (c) burnout in longleaf pine.

work as it may overlap the transition and/or droplet stages. The jets produced by this process lack discrete droplets and tend to be larger than droplet ejections, allowing the two to be differentiated. Figs. 2.6a and 2.6b provide examples of gases ejected from the needles. Eruptive jetting can occur in single or multiple directions. Burning of the ejected gases can occur, but the lower light intensity shown in Fig. 6c indicates that burning does not always happen. Physically, eruptive jetting is expected to result from rupture of the cell walls due to gas pressure accumulating in the cells as liquids vaporize.

### 2.3.1.3 Third Stage: Flaming Combustion

The start of the flaming combustion stage is marked by a sustained flame on the needle/leaf. Examples of flaming combustion are shown in Fig. 2.7. The stage starts with ignition (panel a), continues into flaming (panel b), and ends with burnout (panel c). Ignition typically begins near the tip of the sample and spreads from there. The apparent area of the flames tends to increase (see Fig. 2.7b) as heat from the flame increases the rate at which pyrolyzates are released. The flames continue until the volatile gas concentration reaches the flammability limit and the flame disappears (i.e., burnout), as shown in Fig. 2.7c. A difference was observed between live and dead fuels in this stage – dead fuels display greater maximum flame height and visible flame intensity.

Presumably, the water vapor released during the burning of live fuels dilutes the concentration of pyrolyzates, leading to lower temperatures.

#### 2.3.1.4 Fourth stage: Smoldering combustion

Reactions often continued as smoldering combustion after the flaming stage. As shown in Fig. 2.8, there was no flame, but burning continued, as evidenced by continued visible light emissions from the surface of the needle or smoke. The end of smoldering combustion is the “extinction” point when the burning stops. Ignition occurred without flames in some species (e.g., white spruce, pacific yew, and sagebrush). Ignition was identified by smoke or light emitted by the foliage.

#### 2.3.2 Surface temperature for different stages of burning

Temperature measurements were collected from bundles of heated longleaf pine needles to better understand the influence of temperature on the various stages leading up to and following ignition. These measurements were matched with a visual assessment of the ignition stages in order to correlate the two. Longleaf pine needles were selected because their relatively thick structure (i.e., 1.4 mm thickness) allowed the thermocouple to be bound to them so that

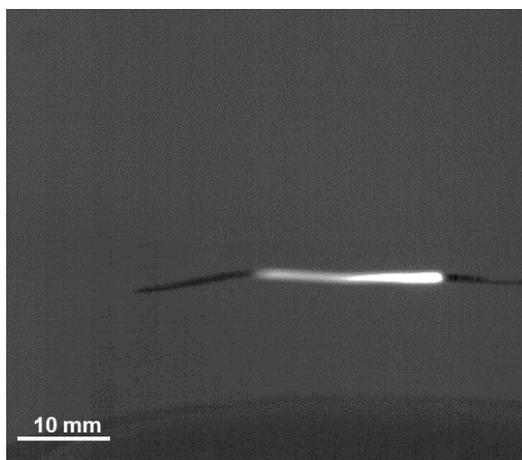


Figure 2.8 An example of smoldering combustion in the western larch needle.

the thermocouple tip was generally in contact with the surface and not exposed directly to the exhaust gases. A pre-calibrated grounded type-K thermocouple with a 3 mm diameter sheath was used. With this approach, the temperatures are considered qualitative estimates of the surface temperatures. Nonetheless, a correlation between the different stages and the temperature of the needles is evident.

Figure 2.9 shows the temperatures of the needles as they were heated and transitioned through the four ignition and burning stages. The first stage (droplet burning) occurred at a temperature of roughly 80°C to 100°C. This temperature range shows that droplet burning and water vaporization happened simultaneously. After the droplet burning stage terminated, the temperature increased during the transition stage. Subsequently, flaming combustion of the samples was observed near temperatures of 310 °C to 350 °C.

The estimated temperature of the needles continued to increase until near 600 °C. The smoldering stage then occurred with relatively few changes in the estimated surface temperature. The surface temperatures of longleaf pine were compared to the results of Diitenberger et al. (2018), who reported surface temperatures of the same fuel as it was heated using cone calorimetry. The variation of surface temperatures in Fig. 2.9 follows the surface temperatures in the results in Diitenberger et al. (2018). Surface temperatures in the current and former work increase after ignition to reach 600 °C. Finally, the variation of surface temperatures shows an approximately constant surface temperature of about 700 °C in Fig. 2.9 in the smoldering stage, similar to the results in Diitenberger et al. (2018).

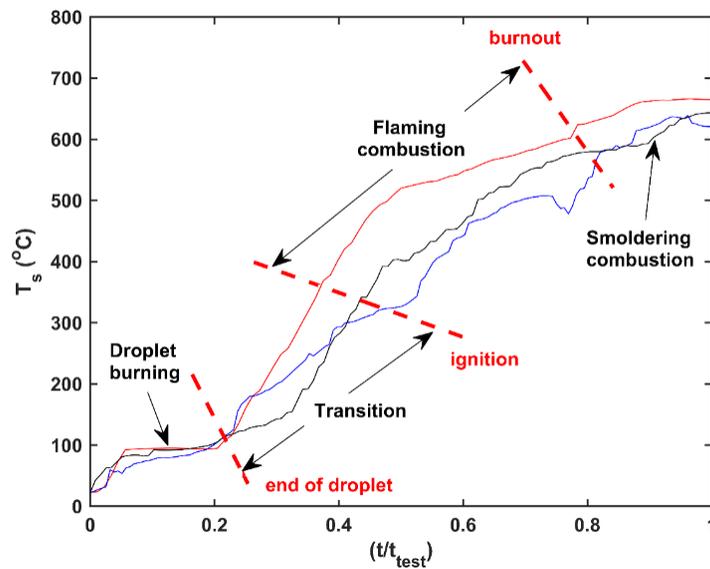


Figure 2.9: The variation of surface temperature ( $T_s$ ) in three samples of longleaf pine with 125% moisture content.

### 2.3.3 The contribution of multi-stages of ignition and burning

Representative high-speed images of the ignition and burning processes of the eight species studied in this work are shown in Fig. 2.10. Each row of Fig. 2.10 includes images illustrating the different ignition and burning stages. More broadly, the four burning stages discussed earlier were observed for longleaf pine, ponderosa pine, Douglas-fir, western larch, and western red cedar needles. For white spruce, all of the stages were observed except for flaming combustion. Transition and smoldering combustion occurred for pacific yew and sagebrush, but the other stages did not. Specific aspects of the ignition process are now highlighted for the various species.

In longleaf pine, ponderosa pine, Douglas fir, western larch, western red cedar, and white spruce, ejection and burning of droplets started almost immediately (within 10 ms) upon the sample being exposed the flame. Figs. 2.10.1.a through 2.10.6.a, show the formation of burning droplets on the needle. The droplets formed on the needle's surface then spread along its length.



In some instances, eruptive jetting occurred during the droplet burning stage, as seen in ponderosa pine (2.10.2.b), Douglas-fir (2.10.3.b), western larch (2.10.4.b), and white spruce (2.10.6.b).

The transition stage was considered to begin when there was no indication of droplet burning, as shown in Figs. 2.10.1.c through 2.10.8.c. Note that pacific yew still exhibited eruptive jetting in this stage. After starting the transition stage, needle discoloration indicated pyrolysis had begun. The end of this transition stage was identified by flaming ignition as shown in Fig. 2.10.1.d to 2.10.5.d or smoldering ignition (visible as smoke) as shown in Fig. 2.10.6.d to Fig. 2.10.8.d. Five species showed flaming combustion, while white spruce, pacific yew, and sagebrush did not. This observation is notable because larger masses of these species display flaming combustion. It seems probable that the concentration of pyrolyzates near the samples was insufficient for flaming ignition. More broadly, the variable reactions of the different species illustrate that both the mass and composition of a species can be essential factors contributing to flaming combustion.

Smoldering was identified in all species, as shown in Fig. 2.10.1.e through Fig. 2.10.8.e. In white spruce, pacific yew, and sagebrush, the smoldering happened directly after the transition stage without any intervening flame. It is assumed that the release rate of pyrolyzates is insufficient for these species to cause a flammable mixture to form.

A brief discussion is provided to summarize what happens at needles/leaf scales during the heating process as fuels are heated, intercellular liquids are heated, and vaporized. Live fuels generally have a moisture content per unit dry weight of  $\sim 100\%$ , which means half of the fresh foliage mass is water. The water inside the foliage is in solution with other compounds. Typically, gas exchange occurs through tiny openings in the foliage called stomata. The

temperature of the foliage remains relatively low (e.g., 100°C) during heating because of the relatively large amount of energy required to raise the water temperature and subsequently vaporize it. For thermally thin fuels, the temperature of the foliage increases after the moisture leaves the foliage. Pyrolysis and subsequent ignition ensue after the temperature of the foliage is sufficient. Further, the external waxy covering of the foliage also evaporates, creating more pathways for vapor to escape. Droplet or eruptive jetting occurs when the mass flux of vapor from the foliage exceeds what can transport through the stomata or the cuticles. The pressure within the foliage increases until the cellular structures rupture, and the vapor causes residual liquids to be rapidly expelled and burn.

#### 2.3.4 Influence of LFMC and heat flux on ignition time and behavior

Figures 2.11 and 2.12 show the variation in ignition time relative to heat fluxes and LFMC for the various species. These results are provided to better understand the influence of heat transfer and fuel moisture content on the time to ignition and the different ignition stages. The LFMC varied among freshly cut, partially dried, and dead samples. For reference, the range of LFMC in live and dried fuels was between 120-155% and 10-116%, respectively. The moisture content for dead fuel was lower than 5%. The estimated convective heat flux range was within 10-95 (kW/m<sup>2</sup>) for longleaf pine, ponderosa pine, Douglas-fir, and western larch, as shown in Fig. 11.d. The heat flux range was within 5-55 (kW/m<sup>2</sup>) for western red cedar, white spruce, pacific yew, and sagebrush, as shown in Fig. 2.12. Note that the same temperatures and exhaust velocities above the burner were used for the experiments; the heat flux varied because of differences in the geometries of the needles. The results are the average ignition times of four tests for each species at a particular moisture content.

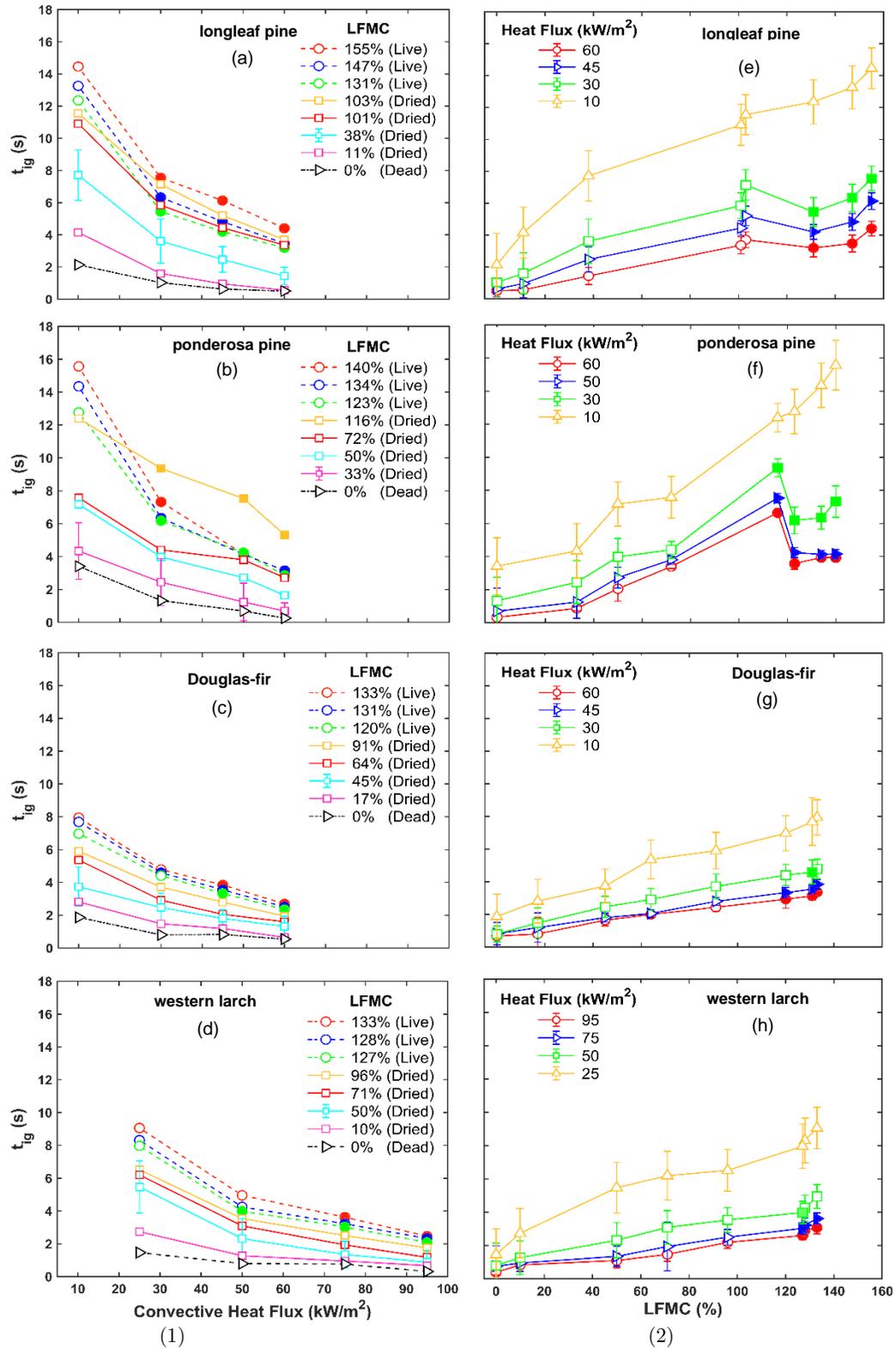


Figure 2.11: The variation of ignition time versus (1) heat fluxes and (2) live fuel moisture content: with (●) and without (○) droplet burning. Same convective conditions (i.e., velocity and temperature) were used for all tests.

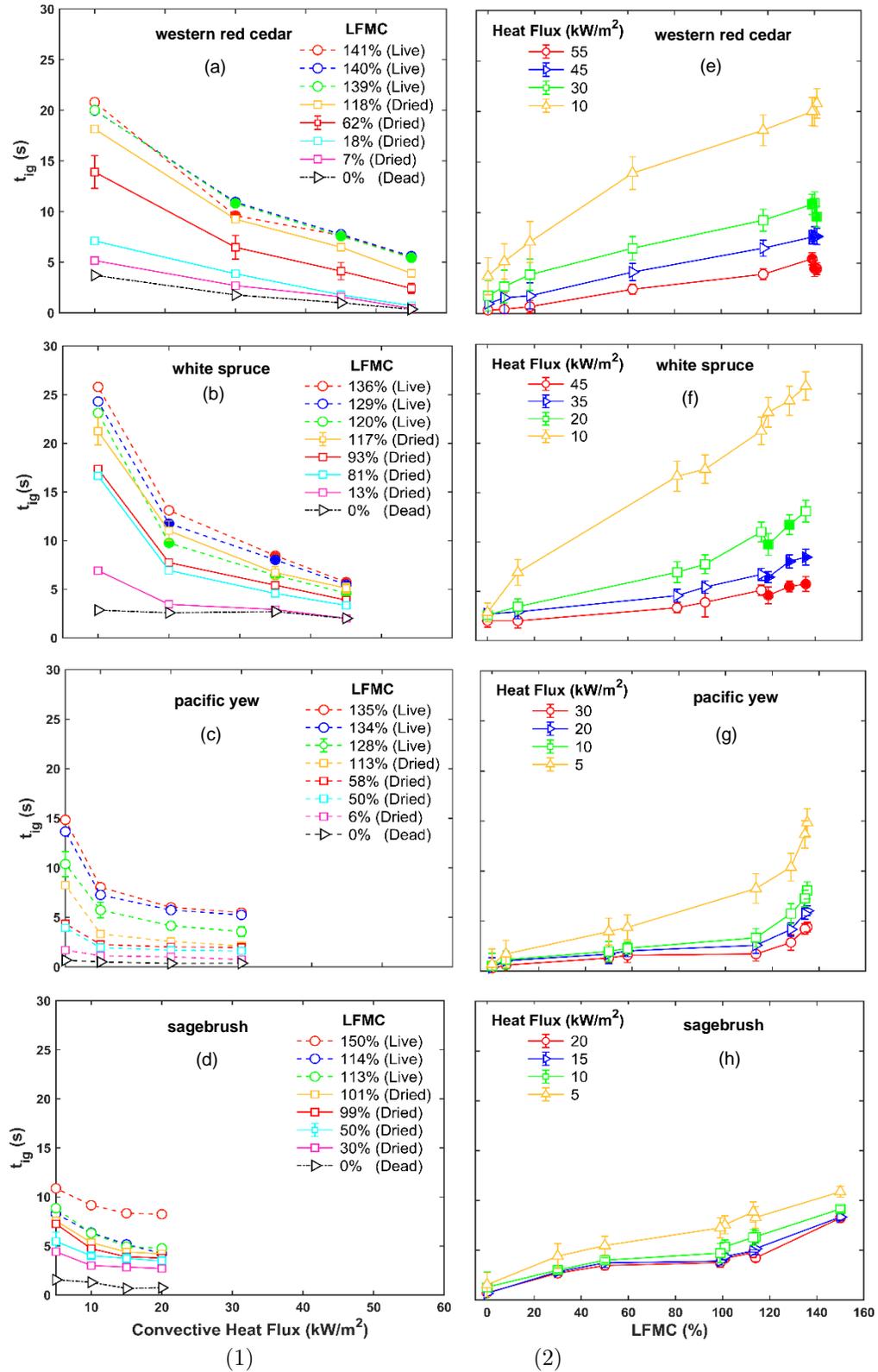


Figure 2.12: The variation of ignition time versus (1) heat fluxes and (2) live fuel moisture content: with (●) and without (○) droplet burning. Same convective conditions (i.e., velocity and temperature) were used for all tests.

The filled symbols ‘●’ indicate conditions whose ignition process contains droplets burning, while non-filled symbols ‘○’ are conditions where no droplets were observed. Representative precision uncertainty bars (95% confidence) are included.

Ignition times decrease with decreasing LFMC for all species, as shown in Figs. 2.11.e through 2.11.h and Figs. 2.12.e through 2.12.h. Decreasing the LFMC reduces the energy required to evaporate the moisture and increase foliage temperature to a level sufficient for pyrolysis to occur. Douglas-fir and western larch usually had shorter ignition times than longleaf pine and ponderosa pine, even at similar (i.e., within 5%) moisture contents. This sensitivity indicates that discrepancies in ignition times can occur because of differences in foliar chemistry.

Droplet burning (represented by filled symbols in Figs. 2.11 and 2.12) appeared for the highest heat flux conditions [i.e.,  $T_g=1025$  K and  $T_g=1010$  K heating cases] and for the highest moisture contents. This observation shows that the moisture within the foliage and the heating rate must be sufficient to cause droplets to be released. If the moisture content or heating rate is insufficient, moisture is released more gradually from the foliage. The only dried fuel that showed droplet burning in its samples was ponderosa pine with LFMC of 116%.

For some species, droplet ejection and burning tend to reduce the ignition times. This reduction in ignition times is evidenced by the inflection in the results (see Figure 2.11 panels e and f; Figure 2.12 p. f). Anecdotally, a reduction in ignition time occurs for species with the greatest ignition sensitivity to the LFMC (e.g., ponderosa pine and longleaf pine). Droplet burning, however, does not tend to reduce ignition times for species whose ignition times

are less sensitive to moisture content (e.g., Douglas-fir and western larch needles).

### 2.3.4.1 Ignition sensitivity of live and dead fuels

An ignition sensitivity index (ISI) was developed to quantify the sensitivity of a given species' time to ignition between the highest and the lowest convective heat fluxes.

For needle-type:

$$ISI = \frac{4.0\Delta t_{ig}\Delta q''}{\overline{\rho c_p} D \Delta T_g} \quad (2.5)$$

while for leaf-type,

$$ISI = \frac{2.0\Delta t_{ig}\Delta q''}{\overline{\rho c_p} W \Delta T_g} \quad (2.6)$$

Here,  $\rho$  is the density of live fuels (360-0.540 kg/m<sup>3</sup>) and dead fuels (380-650 kg/m<sup>3</sup>) (Byram & Fons, 1952),  $\overline{c_p}$  is the average specific heat capacity of fuels between the lowest and highest heat fluxes (i.e., the specific heat capacity of fuels depends on changing temperature) (Byram & Fons, 1952; Boardman et al., 2021),  $\Delta t_{ig}$  is the difference between the highest and the lowest ignition times.  $\Delta T_g$  corresponds to the gas temperature difference between the highest and the lowest heating cases. Ideally, surface temperatures would be used in Eqs. 2.5 and 2.6, however,  $T_g$  is sufficient considering that it is known and influences surface values. Here  $D$  and  $W$  are either the characteristic needle diameter (Eq. 2.5) or the leaf thickness (Eq. 2.6). The factors of 4 and 2 result from simplifying the volume and surface area of the samples in the relationships. Physically the ISI represents the ratio of the heat transfer to the needle (via convection) relative to the rate that the sensible energy of a sample changes.

Hence samples that take longer to heat, either through endothermic reactions or vaporization, would have a larger ISI and should take longer to ignite.

Table 2.1 shows the ISI for the various fuels, live and dead. The ISI values for dead fuels lie between 0.02 and 0.53, while the ISI values for live fuels change in the range of 0.08 to 2.65. The exact values for ISI are not as important as the relative values and trends. Physically, the lower ISI values show that dead fuels have lower sensitivity of ignition to the heat fluxes than live fuels. Energy absorbed by dead fuels more readily changes the sensible energy of the needle. In general, the relatively ranking of ISI values tends to be consistent for a particular species (e.g., highest ISI values for both live and dead fuels, etc.). It is plausible that some of the same consistent remain within the live and dead fuels for a particular species, thus influencing the relative ISI compared to other species. Finally, it is noted that the two live species that did not display droplet ejection (i.e., pacific yew and sagebrush) have the lowest ISI among live fuels. This sensitivity is attributed to heat from convection more readily changing the sensible energy of the needle instead of causing droplet ejection.

Table 2.1 The ignition sensitivity of live and dead fuels relative to the highest and lowest heat fluxes.

Label	Species	live fuel				dead fuel			
		$t_{ig,H}$ (s)	$t_{ig,L}$ (s)	$\Delta t_{ig}$ (s)	ISI	$t_{ig,H}$ (s)	$t_{ig,L}$ (s)	$\Delta t_{ig}$ (s)	ISI
LP	longleaf pine	4.4	14.5	10.1	1.13	0.5	2.1	1.6	0.17
PP	ponderosa pine	3.2	15.6	12.4	1.61	0.3	3.4	3.1	0.38
DF	Douglas-fir	2.7	7.9	5.2	0.73	0.5	1.9	1.4	0.19
WL	western larch	2.5	9.1	6.6	2.65	0.3	1.5	1.2	0.41
WC	western red cedar	5.4	20.8	15.4	2.29	0.4	3.7	3.3	0.53
WS	white spruce	5.5	25.8	20.3	1.04	2.0	2.9	0.9	0.07
PY	pacific yew	4.2	14.8	10.6	0.68	0.3	0.7	0.4	0.02
SB	sagebrush	8.2	10.9	2.7	0.08	0.7	1.6	0.9	0.03

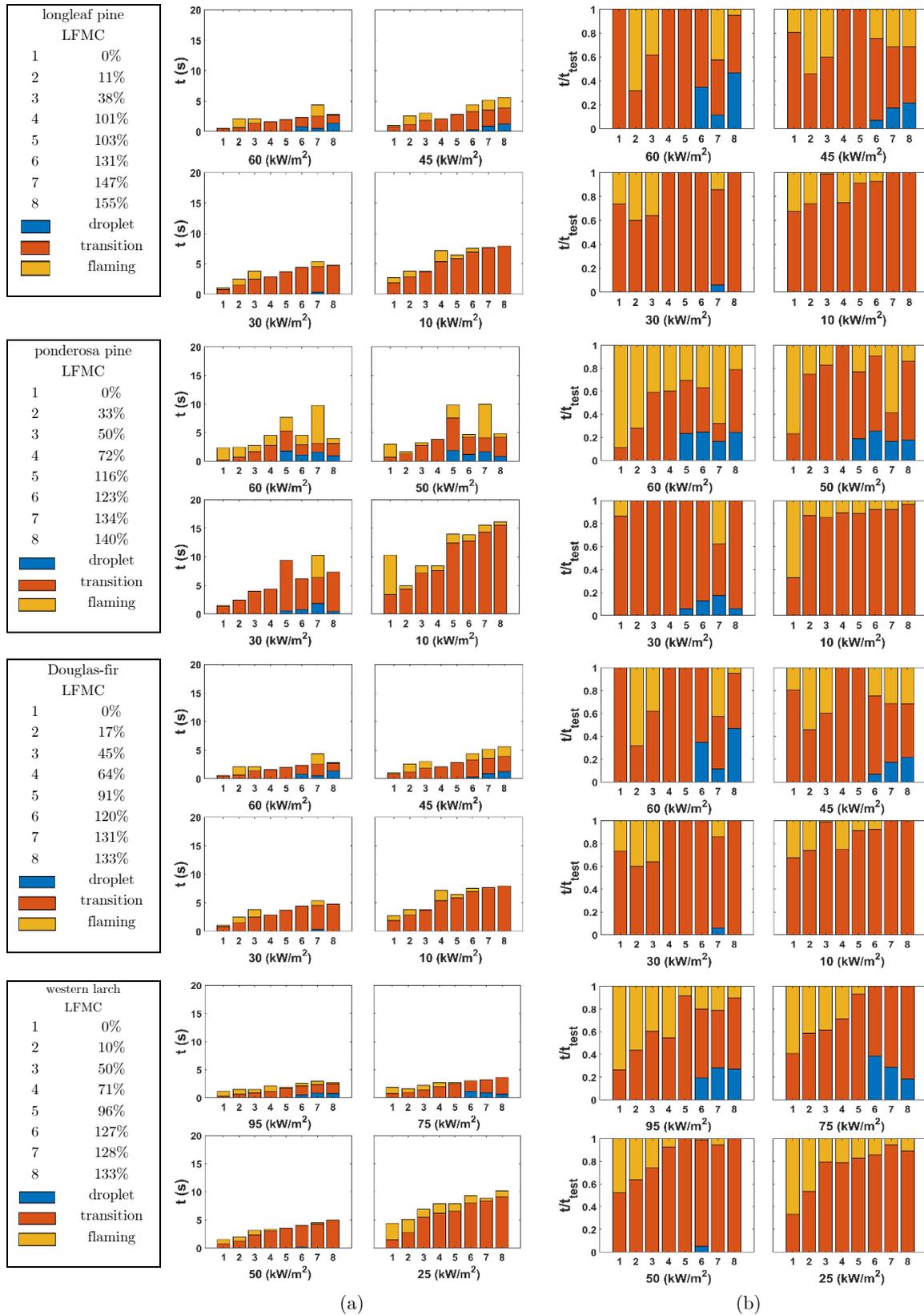
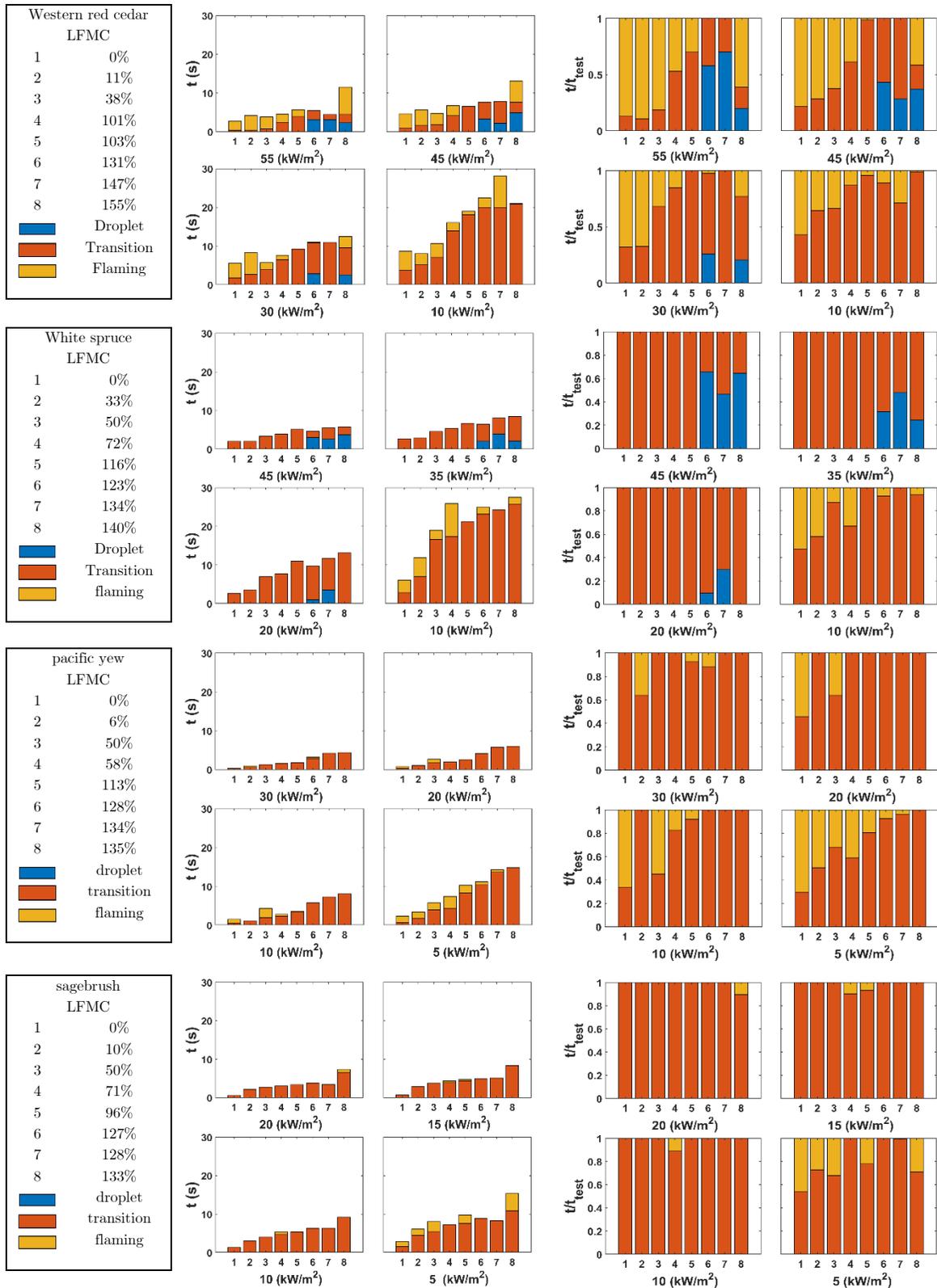


Figure 2.13: The times (column a) and normalized times (column b) associated with the different stages of ignition and burning. The results are reported for different heat fluxes.



(a)

(b)

Figure 2.14: The times (column a) and normalized times (column b) associated with the different stages of ignition and burning. The results are reported for different heat fluxes.

### 2.3.5 The influence of multi-stages on burning

The average times associated with the different stages of ignition and burning were analyzed and are reported in Figs. 2.13 and 2.14. The left and right columns of the figures show the average specific and normalized times, respectively. Note that smoldering burning is not included in the time-scales because of challenges in identifying when smoldering concludes.

The droplet burning stage typically lasted less than 1.0 second when it occurred. The times associated with the droplet stage typically fell between 5% and 45% of the test time (i.e., inset of the needle until flaming concluded or smoldering started). In a few instances, the droplet stage took up 60% of the time. The results show that sufficient moisture needs to be present for droplet burning or ejection to occur; presumably, moisture is needed to cause cellular ruptures within the foliage. For the third heating case (corresponding to free stream  $T_g = 930$  K), the occurrence of droplet burning varied for each species and was less consistent.

The transition stage occurred for all species. Pyrolyzate concentration and temperature increase until they reach ignitable conditions. The transition stage took up from 30% to 80% of the overall time, but typically more than 50% of the time from insertion to completion of flaming, as shown in Figs. 2.13 and 2.14. In a few instances, the transition stage took up 100% of the time because the samples smoldered, and the duration of the smolder was not reported. In general, the transition stage time declines with decreasing species moisture content in time and normalized time, as shown in Figs. 2.13 and 2.14. A decrease in heat flux leads to an increase in the transition stage's duration, as the greater time required to achieve an ignitable temperature would predict. In the all species time-based bar chart shown in Fig. 2.13 and 2.14, with decreasing convective heat transfer, the duration of the transition time for heat

fluxes covered a significant portion of the test time in the fourth heating case (i.e.,  $T_g=700$  K). The results for all species show that when LFMC was larger than 30% the transition stage took a significant portion (>50%) of the test time, while in the third and fourth heating cases, the transition stage took a similar amount of time at all levels of LFMC, even in the dead fuel samples.

The flaming combustion stage did not happen in all test results shown in Figs. 2.13 and 2.14. The occurrence and duration of the flaming stage varied notably depending on the species, LFMC, and heat flux. In lower LFMC samples, the flaming stage took longer than the transition stage. For example, in the conditions with the highest convective heat flux, longleaf pine, ponderosa pine, and western larch experienced flaming. Under the same freestream conditions, flaming combustion was incomplete in other species, which shows that the possibility of flaming combustion depends on heat flux and LFMC, except in the case of white spruce, in which flaming occurred in the lowest heating cases. The duration of flaming combustion decreases from the first heating (i.e.,  $T_g=1025$  K) to the third heating cases (i.e.,  $T_g = 930$  K) in all species except pacific yew. In contrast, the fourth heating case (i.e.,  $T_g = 700$  K) in all species shows an increase in the possibility of flaming combustion. Note that the fourth heating case (i.e.,  $T_g = 700$  K) did not show droplet burning in all species. There may be an inverse relationship between droplet burning and increased flaming combustion in the fourth heating case.

## 2.4 Conclusions

This study sought to systematically identify the various stages of ignition and burning in live, dead, and dried fuels relevant to wildfires. The influence of LFMC and convective heat flux on ignition and burning behavior was examined. Four stages leading up to and including burning were observed:

droplet burning, transition, flaming combustion, and smoldering combustion. The time-scale results show that the LFMC and heat flux have a critical impact on the duration of the droplet, transition, and flaming stages.

The specific conclusions of this study are as follows:

1. Ejection and subsequent burning of droplets can occur prior to sustained flaming ignition only in live fuels. The LFMC and heating flux must be sufficient to induce droplet ejection. Presumably, this is due to differences in the cellular structure and/or plant morphology of live, dried, and dead fuels.
2. Droplet ejection and burning can lead to a reduced time to ignition for live fuels relative to dried fuels with lower LFMC in some species (longleaf pine needle, ponderosa pine, and white spruce). This decreased time to ignition may be attributed to the flammable materials being more broadly distributed (as droplets surrounding the needles). However, in other species, either no droplet burning is observed (e.g., sagebrush, pacific yaw), or the time to ignition is not reduced even when droplet ejection occurs (e.g., white spruce and Douglas-fir).
3. In general, the transition stage tends to take longer than the flaming and droplet stages (when these occur). During the transition stage, the fuels are heated, and pyrolysis occurs. An exception is the conditions with higher heat fluxes (e.g.,  $60 \text{ kW/m}^2$ ) and lower moisture contents (e.g.,  $< 30\%$ ); in these situations, flaming combustion can take longer than the transition time.
4. Both the time-scales to ignition and the different stages of ignition and burning vary more among live fuels than dead and dried fuels. This conclusion indicates that other parameters, such as chemical composition

and structural morphology of the fuel, can significantly influence the burning of live fuel.

5. Ignition time is much more sensitive to the heat flux in live fuels than dead ones. This was evident from the ignition sensitivity index. The ignition sensitivity index shows that dead fuels demonstrate lower sensitivities to changes in heat fluxes.

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## Impacts of Chemical Compositions and Seasonal Variability on Ignition and Burning of Live Fuels

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### Chapter 3: Impacts of Chemical Compositions and Seasonal Variability on Ignition and Burning of Live Fuels

#### Abstract

Wildland fire is a major global that can impact ecosystems and communities worldwide. Many wildfires burn in a mixture of living and senescent vegetation. Therefore, it is necessary to study the burning behavior of live fuel to support fire management decisions. This study investigates the influence of chemical composition (i.e., crude fat concentration) and seasonal variability on the ignition and burning of four living conifer species. The species studied include long-leaf pine (*Pinus palustris*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*). The live fuel moisture content (LFMC), crude fat concentration, time-to-ignition, time-scales of different stages of ignition, and burning of live fuels under the constant heating conditions (i.e., various convective heat fluxes) are reported. Finally, Douglas-fir samples were analyzed to find different chemical compounds such as crude fat, crude protein, ash, structural carbohydrate, and non-structural carbohydrate. The variation of crude fat concentration, live fuel moisture content, time-to-ignition, and the time-scale of live fuel burning was presented. In addition, the impact of seasonal variability on the ignition and burning behavior of the live fuel was investigated. The results show that the ignition time is impacted by seasonal variability due to

the changing of LFMC, and crude fat concentration, but there is no straightforward relationship to generalize between all species.

Keywords: *live fuel, foliage chemistry, moisture content, crude fat, ignition*

### 3.1 Introduction

Wildfires are known for their unpredictability and uncontrollability. Therefore, predicting and managing wildfires is still a challenge for firefighters since there is a significant error in the prediction of fire progress in wildland fires. This error is derived from, in part, inaccurate presumption that live fuels can be modeled as a combination of water and dead fuels (i.e., dry wood). In actuality, the ignition of live fuels is much different from and more complex than that of dead fuels (Jolly & Butler, 2015). Hence, having a high-precision fire model incorporating this complex reality is crucial to the better prediction and management of wildland fires (Weise & Wotton, 2010). Thus, before construction of this high-precision model, an understanding of parameters impacting on wildfire ignition and spread is necessary (McAllister & Weise, 2017). Additionally, the influence of parameters such as live fuel moisture content (LFMC), foliar chemistry (i.e., foliage chemical compositions), and seasonal variability on ignitability and flammability of live fuels needs to be better understood prior to updating and subsequently validating models (Jolly & Butler, 2015).

Previous studies have sought to identify a relationship between moisture content, ignition time, and burnout time of live fuels (Xanthopoulos & Wakimoto, 1993; Dimitrakopoulos & Papaioannou, 2001; Weise et al., 2005; Fletcher et al. 2007; Pickett et al., 2010; Jervis et al. 2010; Cohen & Finney, 2010; Ramadhan et al. 2021). However, these studies have not thoroughly considered the impact of foliage chemistry on the ignition and burning of live fuels (Jolly & Butler, 2015). Although they found several correlations between ignition and LFMC (McAllister et al., 2012), those correlations were insufficient to predict fire ignition and spread in an actual wildland fire (Jolly & Butler, 2015; Alexander & Cruz, 2013). The authors suggested that the LFMC is not

the only parameter influencing ignition and burning in wildland fires and that other effective parameters such as foliar chemistry, and seasonal variability should be investigated (Jolly & Butler, 2015; McAllister & Weise, 2017).

The foliage chemistry of live fuels consists of several chemical components categorized into four main groups: carbohydrates, fats, proteins, and inorganics (i.e., ash) content (Johnson & Kiyoko 2001; Finney et al. 2012). Structural carbohydrates, including cellulose, hemicellulose, and lignin, provide stiffness and rigidity to foliage to protect it against the external environment (Finney et al. 2012). Non-structural carbohydrates are composed of sugar and starch and play a critical role in the metabolic process in foliage. Fats consist of various chemical compounds, including oils, resins, waxes, terpenes, tannins, and fatty acids. These constituents provide structural integrity, energy for metabolic processes, and physiological functions in the foliage plant (Johnson & Kiyoko 2001). Proteins are made of enzymes and substrates and are used in the photosynthesis process (Finney et al. 2012). Finally, inorganic contents are related to the mineral matter contained in foliage. Some limited studies have indicated that chemical components have an essential role in the ignitability and flammability of live fuel (Finney et al. 2012). However, it should be noted that the role of chemical composition in the physical process of live fuel ignition and burning still needs further investigation.

Understanding the influence of foliar chemistry and moisture content on burning behavior is complicated because of the seasonal variation of these two parameters (Jolly & Butler, 2015). For instance, non-structural carbohydrates store sugar and starch in the foliage during the springtime. The stored matter increases the foliar dry mass and decreases the LFMC (Jolly et al., 2012, 2016). To better knowledge, a phenomenon known as the ‘Spring Dip’ shows the seasonal changes in foliar chemistry and moisture content during the springtime

(Van Wagner, 1974; Chrosciewicz, 1986; Jolly et al., 2016). In other words, spring dip consists of two periods of changes in moisture contents. The first period refers to a decrease in LFMC before the growth of new needles due to the storage of sugar and starch (i.e., the increase of dry mass), and the second period occurs when LFMC increases after the new growth of needles (Jolly et al., 2016). According to reported data, the probability of crown fires increases during the first period of the spring dip for some fuels. In short, there is still limited knowledge on how the seasonal variability and spring dip impact the ignition and burning of live fuels.

Crude fat is one of the chemical compounds in live fuels whose ignitability and flammability have been investigated in some limited works (i.e., ether extractives) (Philpot and Mutch 1971; Susott 1980; Brown et al. 2003; Alessio et al., 2008; Ormeño et al., 2009; Guo et al., 2010). Crude fat consists of oils, waxes, fats, terpenes, and other compositions (Philpot, 1969), and is an indicator of the total energy content in a foliage plant; the compounds have high energy content. However, the contribution of crude fat to the ignitability and flammability of live fuel is still in doubt (Finney et al. 2012). Some studies argue that crude fat compounds have a significant contribution to the ignition and burning of live fuels (Philpot, 1969; Ormeño et al., 2009; Guo et al., 2010; Brown et al. 2003). On the contrary, other investigations have found that crude fat has little impact on flammability (Bunting et al. 1983; Alessio et al., 2008). In short, crude fat (i.e., ether extractives) remains one of the chemical components in need of further investigation to understand its impact on live fuel ignition and burning.

Ignition and burning of live fuels can occur through several stages, as shown in Fig. 3.1. The occurrence and duration of the stages vary depending on the species, heat flux, and moisture content. The stages can include droplet ejection

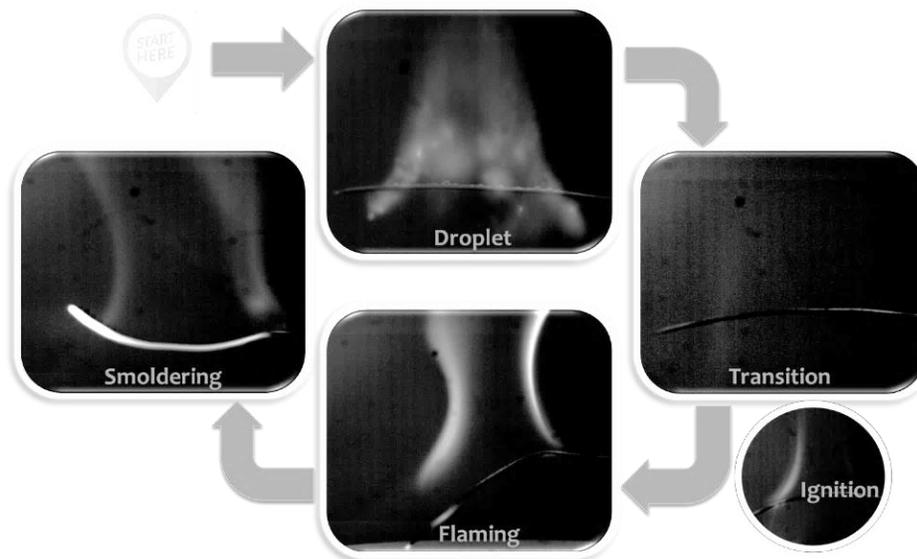


Figure 3.1: The multi-stages of ignition and burning in a longleaf pine needle (Fazeli et al. 2022).

and burning, transition (i.e., pyrolysis), flaming, and smoldering combustion (Fazeli et al. 2022). According to a previous study, some species did not show droplet and/or flaming stage(s) in their ignition and burning processes (Fazeli et al. 2022). Crude fat is one of the chemical components which may have an impact on the ignition and burning stages. Consequently, it is necessary to know how seasonal changes impact the ignition and burning of live fuels.

With this motivation and background, the overall goal of this work is to better understand the impact of foliar chemistry and seasonal variability on the ignition and burning process of live fuels. This goal is accomplished through address four objectives. First, to identify and quantify chemical components of foliage chemistry in live fuels by chemistry analysis. Second, to determine how the stages of ignition and burning change relative to crude fat concentrations and LFMC. Third, to better understand how seasonal changes in crude fat concentration impacts the ignition of live fuels. Fourth, to learn how the ignition

of live fuels is affected by changing of moisture content month to month. It is expected that knowledge gained in this study can be used by the fire community to better understand the impact of chemical compositions and seasonal variability on the ignition and burning of live fuels.

## 3.2 Experimental Approach

### 3.2.1 Experimental Arrangement

A McKenna burner (i.e., flat flame burner) with a mean flame temperature 1025K was operated with a mixture of hydrogen/air at an equivalence ratio ( $\Phi$ ) of 1.24 (Fazeli et al. 2022). Individual needles were held 2 cm above a flat flame burner (FFB), and the resulting ignition and burning processes were recorded using a high-speed camera. The radiation flux from the surface of the burner is negligible because the burner is water cooled. Hence, convection is the primary heat transfer mechanism in the ignition and burning process. A fuel-rich environment (i.e.,  $\Phi > 1.0$ ) is expected for many conditions where flames are near vegetation. A Phantom V711 high-speed camera was used to capture images of the ignition process at a frequency of 1000 frames per second (fps) and an exposure time of 400 ( $\mu$ s). High-speed photos were analyzed to identify different ignition and burning phases and the time-to-ignition.

### 3.2.2 Fuel Collection

The specific species considered included long-leaf pine (*Pinus palustris*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*). These species were considered because of their significance to wildfires, their availability for harvesting, and their contrast in chemical composition. All species were harvested in Corvallis, Oregon (44.5638° N, 123.2794° W), in the United States of America. All live fuel samples

were harvested from a specific tree for each species to minimize foliar chemistry changes that might occur due to differences between individual trees.

There are four stages of ignition and burning in live fuels, including droplet, transition, flaming, and smoldering stages (Fazeli et al. 2022). One of the objectives of this study was to identify how chemical composition (i.e., crude fat concentration) changes during the ignition and burning behavior. Four samples were collected, including fresh (FR), droplet (DR), transition (TR), and flaming/smoldering samples. The fresh (FR) sample refers to live fuels have not yet burnt. The droplet samples were exposed to the flame and pulled away during the droplet time. The droplet time was determined by high-speed camera for each species. The transition samples were collected during the transition time. The flaming/smoldering samples were collected after showing a flame (i.e., flaming stage) or smoke (i.e., smoldering stage) in their burning process.

To evaluate the seasonable variable, samples were harvested and burned between May 2021 to December 2022 (8 months) between the hours of 10 am and 1 pm. All species were considered as fresh (FR) samples collected and burned on the same day.

### 3.2.3 The Measurement of LFMC

The oven-dried method was used to measure the live fuel moisture content of any species used in this study. The samples were placed in an oven at 103°C for four days to dry. The percentage of LFMC as per the dry weight of the sample was calculated using the relationship,

$$\text{LFMC}(\%) = \frac{\text{weight of the liquid in a sample}}{\text{dry weight of a sample}} = \frac{w_{\text{wet}} - w_{\text{dry}}}{w_{\text{dry}} - w_{\text{cont}}} \times 100\% \quad (2.1)$$

where  $w_{\text{wet}}$  is a wet sample,  $w_{\text{dry}}$  is the weight of a dry sample, and  $w_{\text{cont}}$  is the weight of the container.

### 3.2.4 The Measurement of Crude Fat Concentration

The oven-dried samples were used to measure the crude fat concentration. The samples were ground using a Wiley Mill, and a fat filter bag (Ankom XT4) was used to extract crude fat. For each sample, the filter bag was weighed before the extraction process. Then filter bags were filled with about 1.5g of each sample, and the sample weight was recorded. Three bags were measured out for each sample. Crude fat extraction was done using the Ankom XT15 (Ankom, Macedon NY). For each run, 12–15 bags were randomly selected. A reference sample was included in every other run. The bags were oven-dried at 102°C for 3 hours and then weighed, and this weight was recorded as a pre-extraction weight. The bags were placed in the extraction vessel and subjected to petroleum ether extraction for 60 min at 90 °C. For post-test, the bags were oven-dried for 15 min and then reweighed until nine extraction runs were completed.

$$\begin{aligned} \text{CF}(\%) &= \frac{\text{different weight of pre and post extraction sample}}{\text{wet weight of the sample}} & (3.2) \\ &= \frac{w_{\text{pre}} - w_{\text{post}}}{w_{\text{wet}}} \times 100\% \end{aligned}$$

where  $w_{\text{pre}}$  is the weight of sample at pre-extraction,  $w_{\text{post}}$  is the weight of sample at post-extraction, and  $w_{\text{wet}}$  is the weight of wet sample.

## 3.3 Results and Discussion

### 3.3.1 Foliar chemistry of dried Douglas-fir

The foliar chemistry of a Douglas-fir sample was obtained by an external testing laboratory. The chemical analysis, shown in Table A.1, provides the foliar chemistry of a dried Douglas-fir with 8.6% of moisture content and 91.4%

of dry mass. Neutral detergent fiber (NDF) as quantification of structural carbohydrates (SC) was calculated as follows (McAllister et al. 2012):

$$\text{NDF} = 100\% - (\text{NFC} + \text{CF} + \text{CP} + \text{AC}) \quad (3.3)$$

where, non-fiber carbohydrates (NFC) show the non-structural carbohydrate (NSC), crude fat (CF), crude protein (CP), and ash content (AC).

### 3.3.2 Moisture content and foliage chemistry of live fuel in different stages of ignition and burning

The variation of LFMC and foliage chemistry of live fuel during any stages of ignition and burning are shown in Fig 3.3. The changing of moisture content in different stages of ignition and burning is shown in Fig.3.3a.

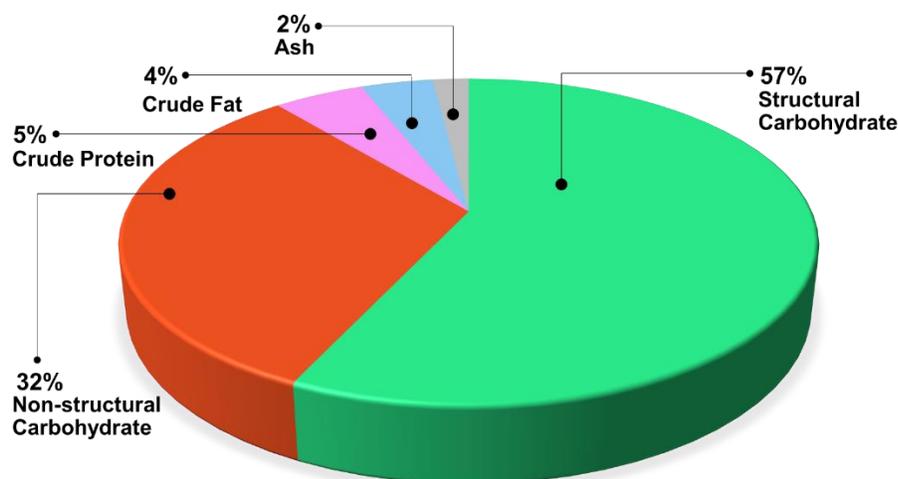


Figure 3.2: Chemical components of foliage chemistry of Douglas-fir.

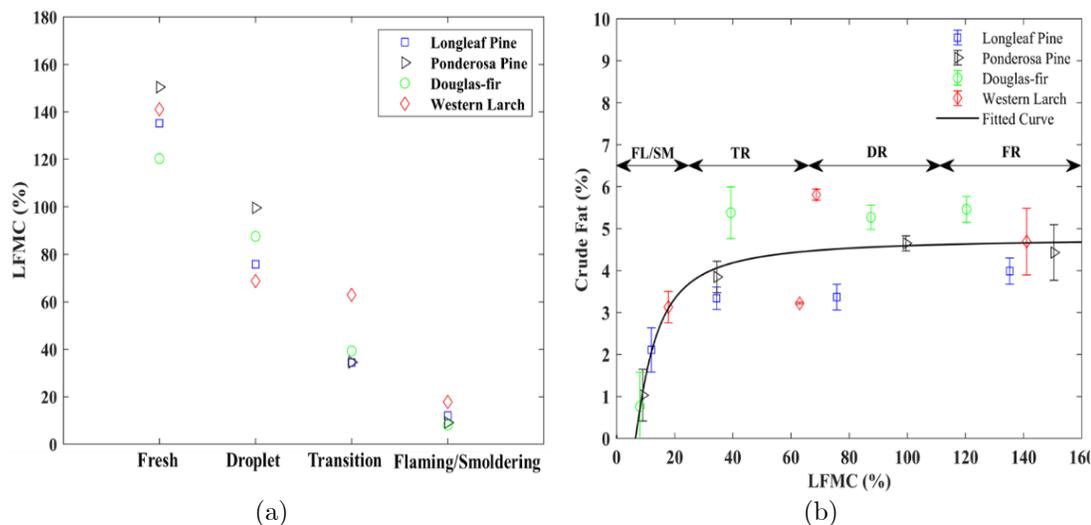


Figure 3.3: The variation of live fuel moisture content (a), and crude fat concentration (b) during different stages of ignition and burning of four live fuels.

The fresh (FR) notation indicated the initial amount of live fuel moisture in the fuel prior to heating. As expected, the live fuel moisture content decreased over time between the droplet stage to the lowest values of moisture content at flaming/smoldering combustions. The reduction in LFMC occurs as the samples are dried in the convective environment. Note that the moisture content is below 20% prior to flaming or smoldering combustion. The crude fat concentration changes are presented in Fig. 3.3.b. There is no evidence of crude fat consumption as shown in Fig. 3.3.b in the fresh, droplet, and transition samples. However, crude fat concentration decreases with decreasing LFMC for all species during flaming/smoldering stages, as shown in Fig. 3.3b. The results show that the crude fat is not important in influencing the ignition process of live fuels, while it has a significant impact on the flammability of live fuels.

### 3.3.3 Seasonal changing of ignition associated with crude fat concentration

Figure 3.4 shows the variation in ignition time and crude fat concentration relative to seasonal variation for the various species. These results

are provided to better understand the influence of seasonal crude fat concentration on ignition time. The crude fat concentration varies from month to month in live fuel samples. For reference, the range of crude fat concentration in different live fuels was between 3% and 6%. The heating conditions of the burner were constant across all tests. Note that the same temperatures and exhaust velocities above the burner were used for all experiments with live fuels. The results are the average ignition times from five tests for each species in each month. Representative precision uncertainty bars (95% confidence) are included for ignition time and crude fat concentration. The results appear to show an inverse relationship between crude fat levels and ignition times.

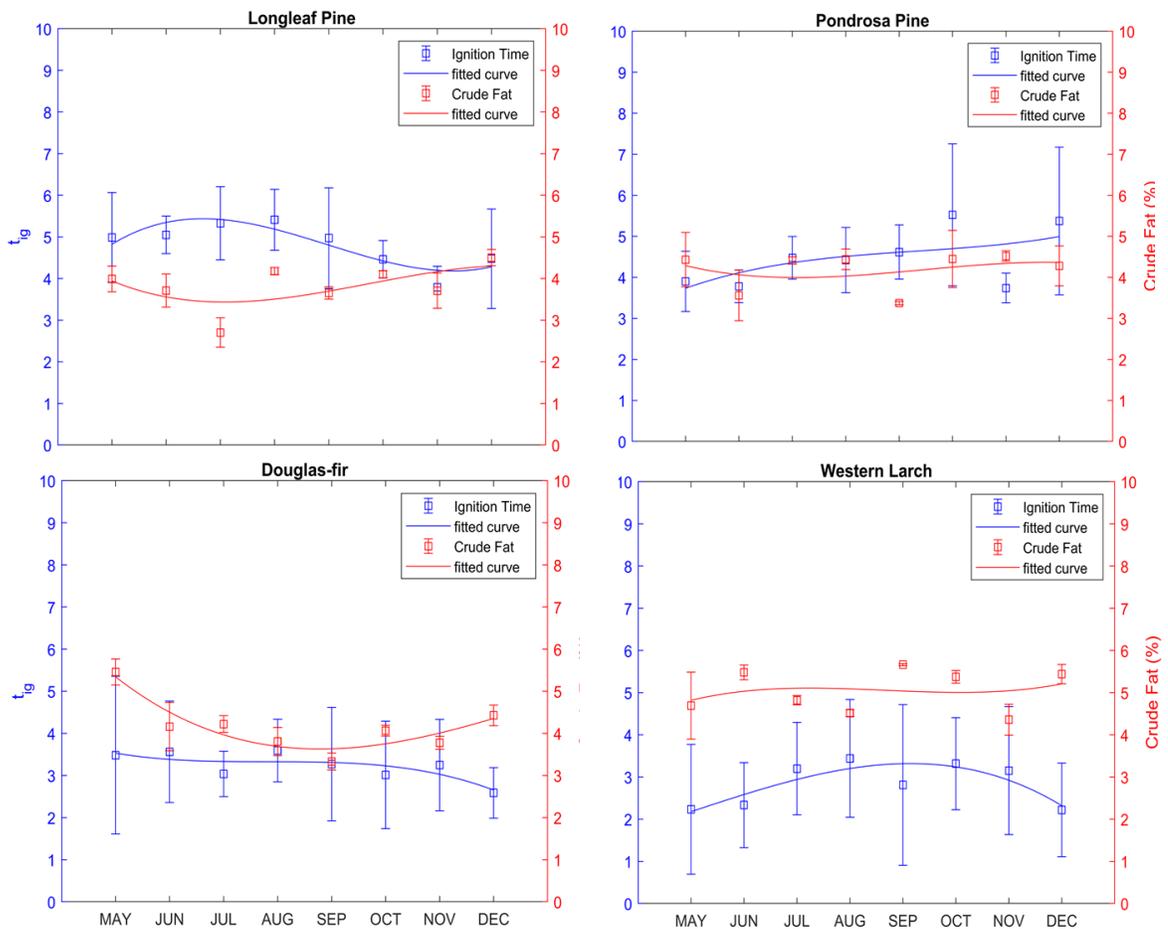


Figure 3.4: The seasonal variation of crude fat concentration and the ignition time of four live fuels.

### 3.3.4 Seasonal changing of ignition associated with LFMC

Changes in ignition time associated with LFMC's seasonal variation were analyzed and reported in Fig. 3.5. Due to the Spring dip phenomenon, a clear increase in LFMC can be observed in all species after May, except for western larch, which shows the Spring dip after June. There is a direct relation between ignition time and LFMC in all species. The ignition time increases when the LFMC increases. It can be mentioned that the LFMC still has a direct relation to ignition time changing in seasonal variability. However, the rate of change in ignition time and LFMC is not constant between all months in all species.

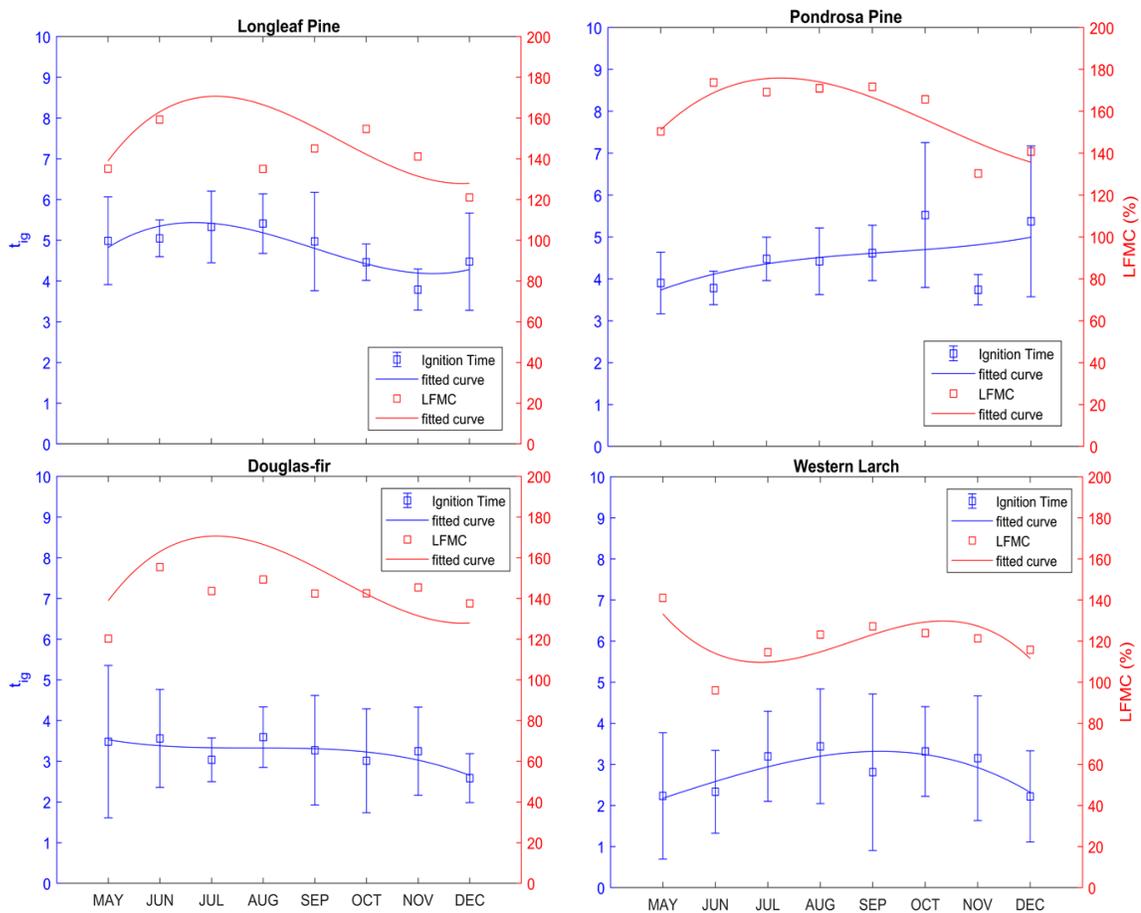


Figure 3.5: The seasonal variation of LFMC and the ignition of four live fuels.

### 3.3.5 Seasonal Changing of ignition and burning stages

The average times associated with the different stages of ignition and burning in the different months were analyzed and are reported in Fig. 3.6. Each column shows the average time associated with the droplet, transition, and flaming stages. Note that the smoldering combustion is not included in the time-scales because of challenges in identifying when smoldering concludes.

The droplet burning stage typically lasted less than 1.0 seconds in all species when it occurred. The times associated with the droplet stage for all species typically fell between 15% and 20% of the total time (i.e., inset of the needle until flaming concluded or smoldering started). The length of the droplet stage was roughly constant for longleaf pine and ponderosa pine at around 1.0 second. The droplet stage times show a small increase in November and October in Douglas-fir and western larch which typically showed a shorter droplet stage than longleaf pine and ponderosa pine.

The transition stage occurred for all species and took up from 65% to 80% of the overall time. In some cases, the transition stage time shows a lower duration, but it can be observed in different months for each species. For instance, the lower transition time can be observed in November for both longleaf pine and ponderosa pine, and in December for both Douglas-fir and western larch. As mentioned before, the ignition time consists of the summation of the droplet and transition stages showing the ignitability. The lower ignition time in Fig. 3.6 indicates that the species reaches the ignition rapidly. Thus, the risk of a plant catching on fire increases when the ignitability decreases.

The duration of the flaming combustion stage indicates the flammability of a plant increases, and subsequently, the risk of high-intensity wildland fire rises. The flaming combustion stage occurs in all tests results except Douglas-fir results as shown in Fig. 3.6. The Douglas-fir results only show one flaming

stage in the October tests. In addition, the time scales of multi-stages shown in October for Douglas-fir show the maximum duration of droplet burning and the minimum duration of the transition stage. In other species, the occurrence and duration of the flaming stage varied notably by month. For both longleaf pine and ponderosa pine, the minimum ignition time can be observed in November. The maximum flaming duration occurred in November for ponderosa pine and in August for longleaf pine. Western larch's minimum ignition time was observed in May, and the maximum duration of the flaming stage occurred in September.

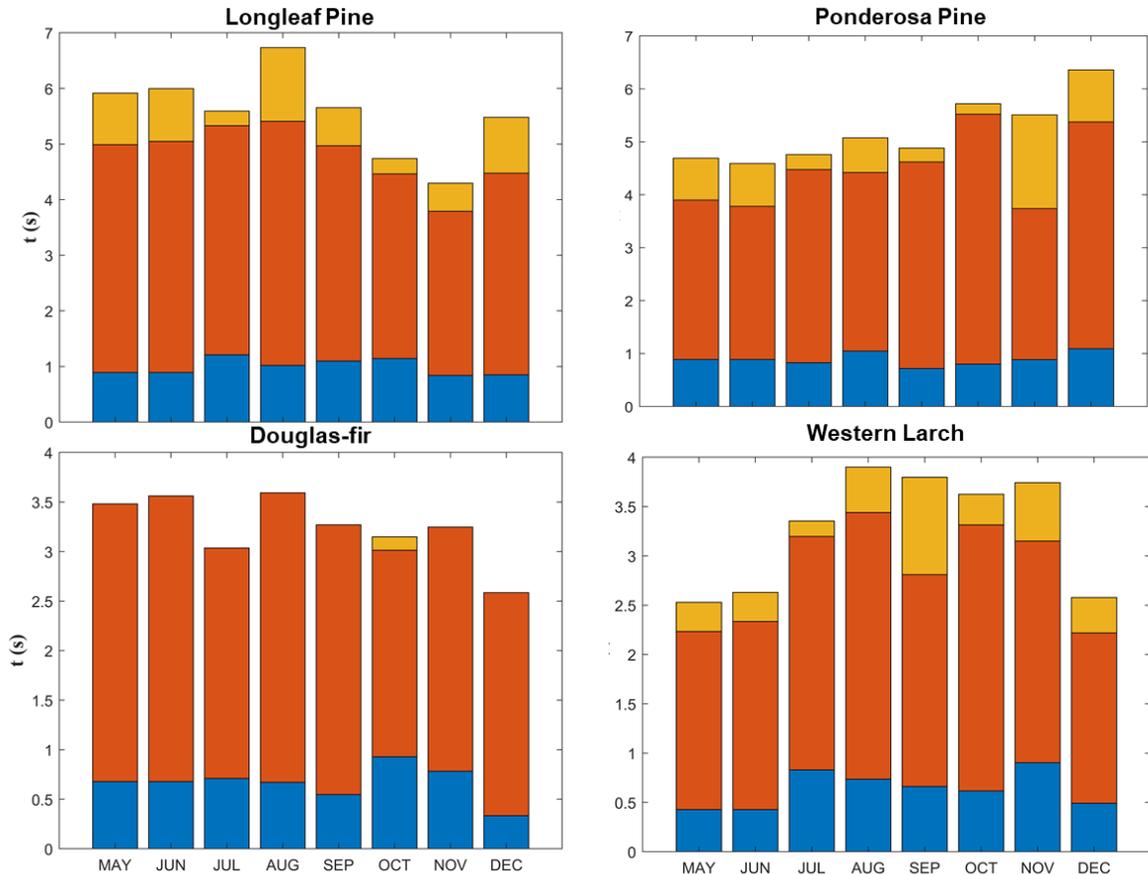


Figure 3.6: The seasonal variation of multi-stages of ignition and burning of four live fuels.

droplet, transition, and flaming.

### 3.4 Conclusions

This study sought to identify the influence of foliage chemistry (i.e., crude fat concentration) and LFMC on the ignition and burning behavior of live fuels. Changes in crude fat concentration and LFMC were studied at different stages of ignition and burning. In addition, the seasonal variability of LFMC and foliage chemistry of live fuel was studied to identify how ignition behavior changes month by month, and the time-scale results show that both LFMC and crude fat concentration impact ignition time and burning behavior. The specific conclusions of this study are as follows:

1. There is no evidence of crude fat consumption in droplet and transition stages, while the study shows that the majority of crude fat concentrations are consumed during flaming and smoldering stages.
2. The impact of seasonal variability on ignition time is significant in all species, but there is no consistent trend to generalize for all species.
3. The crude fat concentration is not a significant chemical compound in seasonal variability studies as evident by the consumption of crude fat after ignition stages (i.e., flaming and smoldering combustion).
4. The LFMC and crude fat concentration are not effective parameters to be studied in seasonal variability according to the results other chemical components should be studied accordingly.

## Chapter 4: Conclusions and Future Works

### 4.1 Summary

This research sought to identify important physical and chemical processes involved in the ignition and burning of live fuels relevant to wildfires. In the study, the influence of live fuel moisture content and convective heat flux on ignition and burning behavior was investigated. Four stages of ignition and burning were identified: droplet burning, transition, flaming combustion, and smoldering combustion. The time-scale of different stages in terms of live fuel moisture content and heat fluxes were presented. The influence of moisture content and heat fluxes on the duration of the droplet, transition, and flaming stages was examined. In the chemical study, the influence of foliage chemistry (i.e., crude fat concentration) and LFMC on the ignition and burning behavior of live fuels were investigated. The changing of crude fat concentration and LFMC in different stages of ignition and burning were studied to identify how those parameters impact on ignitability and flammability of live fuels. In addition, the seasonal changes of LFMC and crude fat concentration in four species were studied to identify how ignition time changes month by month.

The time-scale results showed that there is a relation between LFMC and crude fat concentration on ignition time and burning behavior.

## 4.2 Conclusions

### 4.2.1 Stages of ignition and burning of live fuels

One of the specific conclusions of this study is about observing ejection and subsequent burning of droplets that can occur prior to sustained flaming ignition in live fuels. The LFMC and heating flux must be sufficient to induce droplet ejection. Presumably, the sensitivity is due to differences in the cellular structure and/or plant morphology of live, dried, and dead fuels. Droplet ejection and burning can lead to a reduced time to ignition for live fuels relative to dried fuels with lower LFMC in some species (longleaf pine needle, ponderosa pine, and white spruce). This decreased time to ignition may be attributed to the flammable materials being more broadly distributed (as droplets surrounding the needles). However, in other species, either no droplet burning is observed (e.g., sagebrush, pacific yaw), or the time to ignition is not reduced even when droplet ejection occurs (e.g., white spruce and Douglas-fir). In general, the transition stage tends to take longer than the flaming and droplet stages (when these occur). During the transition stage, the fuels are heated, and pyrolysis occurs. An exception is the conditions with higher heat fluxes (e.g., 60 kW/m<sup>2</sup>) and lower moisture contents (e.g., < 30%); in these situations, flaming combustion can take longer than the transition time. Both the time-scales to ignition and the different stages of ignition and burning vary more among live fuels than dead and dried fuels. This conclusion indicates that other parameters, such as chemical composition and structural morphology of the fuel, can significantly influence the burning of live fuel. Ignition time is much more sensitive to the heat flux in live fuels than in dead ones. This was evident

from the ignition sensitivity index. The ignition sensitivity index shows that dead fuels demonstrate lower sensitivities to changes in heat fluxes.

#### 4.2.2 Foliage chemistry and seasonal variability of ignition and burning in live fuels

There is no evidence to prove that crude fat was consumed in the droplet and transition stages. The results show that most of the crude fat was consumed during the flaming and smoldering stages. The impact of seasonal variability on ignition time is considerable in all species, but there is no specific trend to generalize for all species. The crude fat concentration has no significant impact on seasonal variability study due to the consumption of crude fat after ignition stages (i.e., flaming and smoldering combustion).

### 4.3 Recommendations for Future Works

The recommended future works to continue this study are as follows:

1. The dried samples (i.e., live fuel was dried for several days) did not show both droplet burning and eruptive jetting, while some dried samples still had a moisture content of more than 100%. The volatile loss is one of the reasons that may be happened for not observing droplet burning and eruptive jetting in the dried sample with enough moisture content (>100%). It is necessary to analyze the chemical compounds of volatiles to learn more about droplet burning and eruptive jetting.
2. The chemical analysis of non-carbohydrates such as sugar and starch is a potential investigation to identify how they contribute to the ignitability and flammability of live fuels.
3. Microscopic studies regarding foliage structural changes would help to understand the impacts of ignition and burning on cells of a needle\leaf.

It would show how moisture content and other chemical compounds may change during different stages of ignition and burning. In addition, the microscopic study would demonstrate what happens to cells during eruptive jetting.

4. This experimental approach used in this work can be applied to understand the changes in burning and ignition behavior as fuel transitions from being new to mature growth needles on the ignition and burning behavior. The chemical analysis can be carried out for both old and new needles to identify the difference between them in terms of chemical composition.
5. Other heat transfer mechanisms such as radiation heat transfer and a combination of convection and radiation heat transfer are potential research to identify the ignition and burning behavior in live fuels. The radiation heat transfer plays a pre-heating role in a real wildland fire. Radiation heat transfer decreases the ignition time, and we need to know how it impacts different stages of the ignition and burning process.
6. The pyrolysis of live fuel begins in the transition stage. The potential study is to investigate how different heat fluxes (i.e., mean flame temperature), moisture content, and foliage chemistry impact pyrolysis products of live fuels.

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## Appendices

Appendix-A.1 List of Plant Species Evaluated in This Study

Appendix A.2 Different Convective Heat Fluxes

Appendix-A.3 Foliar Chemistry of a Dried Douglas-fir

Appendix-A.4 Definition of Ignition Sensitivity Index (ISI)

## Appendix-A.1 List of Plant Species Evaluated in This Study

As depicted in Table A.1, seven species of conifer tree and one shrub were evaluated during ignition tests. The specific species considered included longleaf pine (*Pinus palustris*), Douglas-fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), Ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), pacific yew (*Taxus brevifolia*), white spruce (*Picea glauca*), and sagebrush (*Artemisia tridentate*).

Table A.1: List of plant species in the experiments. Some images were obtained from reference (Texas A&M Forest Service, 2022).

Scientific Name	Tree	Live Fuel	Dead Fuel	Scientific Name	Tree	Live Fuel	Dead Fuel
longleaf pine  ( <i>Pinus palustris</i> )				Douglas-fir  ( <i>Pseudotsuga menziesii</i> )			
western red cedar  ( <i>Thuja plicata</i> )				Ponderosa pine  ( <i>Pinus Ponderosa</i> )			
western larch  ( <i>Larix occidentalis</i> )				Pacific yew  ( <i>Taxus brevifolia</i> )			

Table A.1: List of plant species in the experiments. Some images were obtained from Texas A&M Forest Service, 2022 (continued)

Scientific Name	Tree	Live Fuel	Dead Fuel	Scientific Name	Tree	Live Fuel	Dead Fuel
white spruce <i>(Picea glauca)</i>				sagebrush <i>(Artemisia tridentate)</i>			

## Appendix A.2 Different Convective Heat Fluxes

The different heating conditions and the corresponding convective heat fluxes.

Table A.2: Convection heat flux approximation in heating cases for different species

Specie	Nu correlation used	D/W (mm)	$T_m$ (K)	$Re$	$Nu$	$h$ (W/m <sup>2</sup> K)	$T_m - T_s$ (K)	$q''_{conv}$ (kW/m <sup>2</sup> )
longleaf pine (LP)	Cylindrical (Eq. 2.3)	1.4	1025	6.7	1.6	78.6	727	60
			1010	3.9	1.3	62.6	712	45
			930	2.0	1.0	45.9	632	30
			700	0.8	0.7	27.5	402	10
ponderosa pine (PP)	Cylindrical (Eq. 2.3)	1.2	1025	6.1	1.5	83.5	727	60
			1010	3.5	1.2	66.7	712	50
			930	1.8	1.0	49.1	632	30
			700	0.7	0.7	29.6	402	10
Douglas-fir (DF)	Cylindrical (Eq. 2.3)	1.3	1025	6.5	1.5	80.0	727	60
			1010	3.8	1.2	63.8	712	45
			930	1.9	1.0	46.8	632	30
			700	0.8	0.7	28.1	402	10
western larch (WL)	Cylindrical (Eq. 2.3)	0.6	1025	3.0	1.1	129.9	727	95
			1010	1.7	0.9	105.7	712	75
			930	0.9	0.7	79.9	632	50
			700	0.3	0.6	50.1	402	25
western red cedar (WC)	Cylindrical (Eq. 2.3)	1.4	1025	6.8	1.6	78.3	727	55
			1010	3.9	1.3	62.3	712	45
			930	2.0	1.0	45.7	632	30
			700	0.8	0.7	27.4	402	10
white spruce (WS)	Cylindrical (Eq. 2.3)	2.0	1025	9.9	1.8	62.6	727	45
			1010	5.7	1.5	49.5	712	35
			930	2.9	1.1	35.8	632	20
			700	1.1	0.8	21.1	402	10
pacific yew (PY)	Flat plate (Eq. 2.4)	1.2	1025	6.1	0.8	42.1	727	30
			1010	3.5	0.5	29.7	712	20
			930	1.8	0.4	18.5	632	10
			700	0.7	0.2	8.5	402	5
Sagebrush (SB)	Flat plate (Eq. 2.4)	3.8	1025	18.8	1.5	27.1	727	20
			1010	10.9	1.1	19.1	712	15
			930	5.5	0.8	11.9	632	10
			700	2.2	0.4	5.5	402	5

## Appendix-A.3 Foliar Chemistry of a Dried Douglas-fir

Table A.3 Foliar chemistry of a dried Douglas fir sample with chemical analysis.

Chemical Component	Results	Unit	Type of Estimation
Moisture	8.60	%	AOAC 930.15
Dry Matter	91.4	%	AOAC 930.15
Crude Protein (CP)	5.07	%	AOAC 990.03
Crude Fat (CF)	3.54	%	AOAC 920.39
Ash Content (AC)	2.2	%	AOAC 942.05
Non-Fiber Carbohydrates (NFC)	31.80	%	CALCULATION
TDN	68.9	%	AOAC 973.18
ADF Fiber	22.1	%	AOAC 973.18
Starch	15.2	%	AOAC 996.11
Sugar	16.6	%	AOAC 950.01
Non-Structural Carbohydrates	31.80	%	CALCULATION
Estimated Net Energy (ENE)	59.3	ton/cwt	AOAC 973.18
Net Energy Lactation (NEL)	0.717	Mcal/lb	AOAC 973.18
Net Energy Maintenance (NEM)	0.749	Mcal/lb	AOAC 973.18
Net Energy Gain (NEG)	0.489	Mcal/lb	AOAC 973.18
Calcium	0.39	%	FEED METALS
Phosphorus	0.11	%	FEED METALS
Potassium	0.56	%	FEED METALS
Magnesium	0.08	%	FEED METALS
Sulfur	0.06	%	FEED METALS
Sodium	0.01	%	FEED METALS
Iron	26.4	%	FEED METALS
Copper	1.67	%	FEED METALS
Zinc	17.0	%	FEED METALS
Manganese	363	%	FEED METALS

## Appendix-A.4 Definition of Ignition Sensitivity Index (ISI)

An ignition sensitivity index (ISI) was developed to quantify the sensitivity of a given species' time to ignition between the highest and the lowest convective heat fluxes. Physically the ISI represents the ratio of convective heat transfer to the needle (via convection) relative to the rate that the sensible energy of a sample changes.

$$\text{ISI} = \frac{\text{convective heat transfer}}{\text{sensible energy change over ignition time}} \quad (\text{A.1})$$

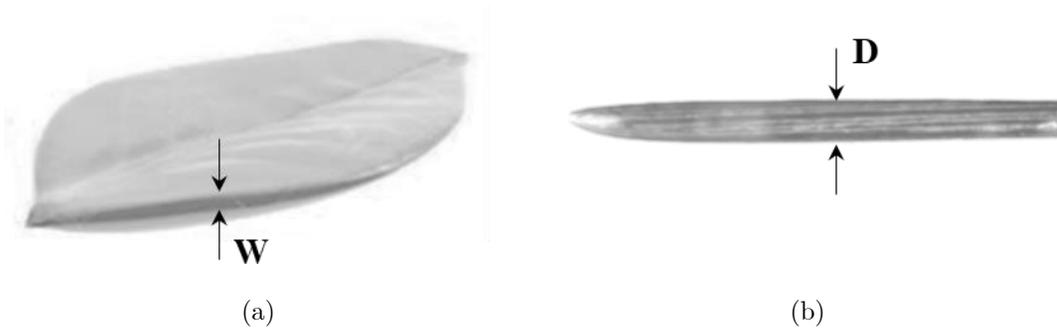


Fig. A.1 The thickness ( $W$ ) and diameter ( $D$ ) of leaf (a) and needle (b) to define ignition sensitivity index (ISI).

The ignition sensitivity index for needle can be given by

$$\text{ISI} = \frac{\Delta q'' A}{\rho \bar{c}_P \Delta T_g V} = \frac{\Delta q'' (\pi D l)}{\rho \bar{c}_P \Delta T_g (\frac{\pi D^2}{4} l)} = \frac{4 \Delta q''}{\rho \bar{c}_P \Delta T_g D} = \frac{4 \Delta q'' \Delta t_{ig}}{\rho \bar{c}_P \Delta T_g D} \quad (\text{A.2})$$

$A$  is convective area of a cylinder exposed to the flame with a length ( $l$ ) and a diameter ( $D$ ).  $V$  is the volume of the needle. The ignition sensitivity index for leaf can be given by

$$\text{ISI} = \frac{\Delta q'' A}{\rho \bar{c}_P \Delta T_g V} = \frac{\Delta q'' (2A_F)}{\rho \bar{c}_P \Delta T_g (A_F W)} = \frac{2 \Delta q''}{\rho \bar{c}_P \Delta T_g W} = \frac{2 \Delta q'' \Delta t_{ig}}{\rho \bar{c}_P \Delta T_g W} \quad (\text{A.3})$$

$A$  is convective area of a flat plate exposed to the flame. The convective area can be obtained by the summation of top and bottom areas ( $A = 2A_F$ ) with a thickness ( $W$ ).  $V$  is the volume of the leaf ( $V = A_F \cdot W$ ).