

FINAL REPORT

Ignition, Propagation, and Emissions of Smoldering Combustion: Experimental Analysis and Physics Based Modelling

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February 2022

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REPORT DOCUMENTATION PAGE						Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.							
1. REPORT DATE (DD-MM-YYYY) 14/02/2022		2. REPORT TYPE SERDP Final Report			3. DATES COVERED (From - To) 9/21/2016 - 9/22/2021		
4. TITLE AND SUBTITLE Ignition, Propagation, and Emissions of Smoldering Combustion: Experimental Analysis and Physics Based Modelling					5a. CONTRACT NUMBER 16-C-0045		
					5b. GRANT NUMBER		
					5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) David Blunck and Kyle Niemeyer: Oregon State University Bret Butler and Wei Min Hao: USDA Forest Service					5d. PROJECT NUMBER RC-2651		
					5e. TASK NUMBER		
					5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Oregon State University 314 Rogers Hall Corvallis, OR 97339					8. PERFORMING ORGANIZATION REPORT NUMBER RC-2651		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Research and Development Program (SERDP) 4800 Mark Center Drive, Suite 16F16 Alexandria, VA 22350-3605					10. SPONSOR/MONITOR'S ACRONYM(S) SERDP		
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) RC-2651		
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.							
13. SUPPLEMENTARY NOTES							
14. ABSTRACT Smoldering combustion plays a dangerous role in many prescribed and wildland fires. Smoldering burns can last much longer (i.e., days to weeks) and provide relatively more smoke and other pollution than flaming burns. For example, Figure 1 shows the smoke being released during a prescribed burn in Silver Lake, OR. An increased ability to predict the spread rate and emission release rate of smoldering burns for a wide range of fuels and conditions is needed to help reduce the detrimental impacts of smoldering burns on humans (e.g., smoke in Figure 1) and the environment. Unfortunately, our ability to understand and predict smoldering behavior is limited to just a few fuels (e.g., peat) and conditions. The overall goal of this effort was to obtain the scientific understanding needed to develop tools for assessing risks of ignition, spread, and emissions from smoldering combustion for fuels and conditions applicable to the DoD.							
15. SUBJECT TERMS Smoldering combustion, emissions, modelling, surrogate							
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UNCLASS	18. NUMBER OF PAGES 122	19a. NAME OF RESPONSIBLE PERSON David Blunck		
a. REPORT UNCLASS	b. ABSTRACT UNCLASS	c. THIS PAGE UNCLASS			19b. TELEPHONE NUMBER (Include area code) 541-737-7095		

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List of Acronyms

OSU	Oregon State University
USDAFS	United States Department of Agriculture Forest Service
DoD	Department of Defense

Keywords

Smoldering combustion, emissions, modelling, surrogate

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Acknowledgments

Support from the following individuals and groups is gratefully acknowledged. Dr. Willie (Skip) Rochefort from Oregon State University's Rheology Laboratory provided training and supplied thermal analysis equipment for evaluation of plant litter. Matt Ellis from the Methow Valley Ranger District (Okanogan-Wenatchee National Forest, Winthrop, WA) facilitated field-scale smoldering research burns. The Nature Conservancy of Oregon permitted the use of land and research equipment during controlled burns. The Deschutes National Forest, Sisters Rangers District (Stephen Mike Bishop) allowed plant litter samples to be collected. Similarly, Carol Carlson from Oregon State University's Research Forest allowed plant litter samples to be collected.

The efforts of multiple undergraduate, graduate, and post-doctoral researchers are mentioned. Benjamin Smucker, Daniel Cowan, Tejas Mulky, and W. Jayani Jayasuriya (graduate students at OSU) conducted laboratory, field, and numerical studies, respectively.

Finally, the support of SERDP in providing funding and technical oversight is gratefully acknowledged. The sustained funding for multiple PIs over 5 years was a tremendous benefit to the technical progress of the project and ultimately to the smoldering community.

Abstract

Introduction and Objectives

Smoldering combustion plays a dangerous role in many prescribed and wildland fires. Smoldering burns can last much longer (i.e., days to weeks) and provide relatively more smoke and other pollution than flaming burns. For example, Figure 1 shows the smoke being released during a prescribed burn in Silver Lake, OR. An increased ability to predict the spread rate and emission release rate of smoldering burns for a wide range of fuels and conditions is needed to help reduce the detrimental impacts of smoldering burns on humans (e.g., smoke in Figure 1) and the environment. Unfortunately, our ability to understand and predict smoldering behavior is limited to just a few fuels (e.g., peat) and conditions. The overall goal of this effort was to obtain the scientific understanding needed to develop tools for assessing risks of ignition, spread, and emissions from smoldering combustion for fuels and conditions applicable to the DoD.



Figure 2. Illustration of negative impact of smoldering combustion: smoke emissions from burn. The burn was part of a prescribed burn by the Nature Conservancy of Oregon near Silver Lake, OR.

Technical Approach

To accomplish the overall goal, this work focused on identifying physical and chemical processes that control smoldering combustion. A series of laboratory studies were conducted where the chemical and physical composition of the fuel beds was systematically changed and the impact on the smoldering behavior quantified. Corresponding calculations were performed using a detailed physics model to obtain additional insights into controlling physical processes. Smoldering burns were also conducted in the field, or by burning field samples in the laboratory. Results from these studies were used to help identify smoldering behavior expected in nature. Finally, emission samples were collected from burns and correlated to smoldering behavior.

Results

Notable knowledge was obtained with regards to the influence of chemical composition and physical structure of the fuel bed on smoldering behavior. A few of these findings are summarized.

When the density is fixed, propagation velocities increase with decreasing cellulose (and increasing hemicellulose) content. This sensitivity is caused by the earlier pyrolysis and higher temperatures that occur when hemicellulose is present in the fuel. When the fuel is loosely packed and the density is not controlled, horizontal propagation velocities increase with increasing cellulose content. This sensitivity is due to the lower densities with higher cellulose contents. Fuels with higher lignin content smolder at slower horizontal and vertical propagation speeds. This behavior is caused by slower pyrolysis and higher activation energy of lignin. Once the fuel is composed of 20-30% lignin, lignin is the dominant chemical component in influencing smoldering propagation behavior due to its slower reaction rates.

Burning of surrogate fuels composed of lignin, hemicellulose, and cellulose can reasonably match horizontal propagation velocities of ground Douglas-fir and wheat straw. However, downward propagation velocities are only similar if the inorganic content is minimal (among

potentially other factors). The differences in downward smoldering may be due to differences in ash layer development.

The physical expansion of fuels caused by moisture causes the propagation speed of smoldering to increase, due to the reduction in density. If the fuel does not expand with the addition of water (i.e., water fills the fuel pores), the propagation speed drops primarily due to increase in wet bulk density. In both cases, additional moisture content reduces the mean peak temperature slightly.

Smaller particles are more prone to self-sustained smoldering and have higher horizontal and downward smoldering spread rates in porous beds with homogenous particle sizes. Limits in self-sustained smoldering based on particles being sufficiently small are not evident, at least within the ranges evaluated in this study (i.e., diameter > 0.5 mm).

Physical properties of duff and peat soils, in particular moisture content, packing density, and mineral content, have been identified as important factors affecting the ignition and propagation of smoldering combustion.

It was found that the emissions factor for CH₄, NMHC, and PM_{2.5} increased with increasing surface temperature and spread rate. However, with respect to emission fluxes, EM, the only significant relationship observed was a muted positive correlation of EMCH₄ and EMNMHC with spread rate.

Anticipated Benefits

At least five major benefits are anticipated as a result of this project. The first major benefit is that this study provides strong evidence that fire managers may be overestimating PM_{2.5} emissions when smoldering duff is expected. If true, fire managers could be unnecessarily limiting much needed use of prescribed fire because of emissions concerns. The emission factors quantified in this study can enable more accurate prediction of pollutant emissions from smoldering duff in prescribed fires. The second impact of this study is that a new methodology and conceptual framework for considering smoldering behavior of natural fuels has been established; this shift in how smoldering behavior is considered has the potential to be transformative. The third implication of this work is a model for considering smoldering of general real fuels has been developed and will be made available. The model can be used by the community to examine smoldering of particular fuels based on composition, in contrast to using a model validated for a specific fuel. A fourth major benefit of this work was pioneering the use of surrogate fuels to emulate key characteristics of natural fuels. Prior research has considered surrogate fuels for other complicated fuels (e.g., jet fuels, diesel). However, the use of surrogate fuels to understand and predict smoldering combustion has not been widely considered. An advantage of using surrogate fuels is that calculations are more tractable and can arguably better capture key physical and chemical processes. Equally important, the use of surrogate fuel has the potential to allow smoldering behavior to be predicted a priori if the constituents and properties of the fuel bed are known. The fifth major implication of this project is further identifying the (significant) role of heat transfer in controlling/influencing smoldering behavior through porous materials. It is expected that this new fundamental insight will be used by the smoldering community to greatly enhance how we explain and understand smoldering.

1. Executive Summary

1.1 Introduction

Managing the impacts of smoldering combustion during prescribed burns and wildland fires is critical to supporting Department of Defense (DoD) missions. Smoldering combustion is significant because it can damage ecosystems, contribute substantially to air pollution and carbon emissions [1–5], affect public health, and transition to flaming combustion [5–7]. A challenge with smoldering combustion is that it can affect both the immediate ecosystem and surrounding regions. In the immediate vicinity, the air, soil, and fauna can be drastically altered because of the high temperatures and removal of litter and duff near the ground. In extreme cases, smoldering can contribute to mortality of mature or old-growth trees [8]. In the regions surrounding a smoldering burn, severe air pollution can occur as smoldering releases more carbon monoxide (CO), methane (CH₄), volatile organic compounds (VOC), and fine particulate matter (PM_{2.5}) on a per mass basis [2, 9]. The environmental impact on the surroundings is further complicated because the smoke produced by smoldering often remains near the surface and disperses slowly in the absence of a convective plume from an adjacent flame front. As a result of the high pollutant production rates and poor dispersion conditions, smoldering combustion frequently impacts adjacent communities by affecting air quality, visibility, and public health [10].

Fire modelling tools that consider ignition, propagation, and pollutant emission characteristics from smoldering combustion are essential to enable informed fire-management decisions. However, current tools for predicting the ignition of smoldering combustion [11–13], as well as the burn duration [11, 14, 15], its impacts on air quality [9, 16, 17], and soil productivity, are severely limited. This hindrance results, in part, from limited knowledge about the controlling processes in smoldering combustion. Prior research has often obtained empirical trends or results specific to a fuel type, such as peat [9, 18–20] or cotton [7, 21], and condition. What is needed are discoveries about the physical and chemical processes that control ignition, propagation, and pollutant emissions of smoldering combustion for all fuel conditions. Such discoveries can enable the development of advanced predictive fire modelling tools.

Physical and chemical processes that control ignition, propagation and emissions can be categorized into: fuel characteristics, scaling, and thermal and mass transport. Smoldering studies have typically investigated aspects of these key processes, but typically only for specific fuels or conditions [9, 11–13, 16, 17, 22–24]. As a result, it is not possible to predict a priori if smoldering ignition or propagation will occur aside from the conditions that were investigated. Parameters that control ignition are not fundamentally well understood and rate limiting parameters are still unknown. For example, recent computations and experiments regarding smoldering combustion of peat provided valuable understanding about the effect of moisture content and what concentrations limit propagation [19, 25–27], yet it was not clear how those findings extend to other fuels, including those significant to DoD.

1.2 Objectives

The overall goal of this effort was to obtain the scientific understanding needed to develop tools for assessing the risks of ignition, spread, and emissions from smoldering combustion for fuels and conditions applicable to the DoD. Note that the focus was on developing the knowledge, not the tools themselves, although several models were developed/refined as part of this work. To

accomplish the overall goal, this work focused on identifying physical and chemical processes that control smoldering combustion through modeling, laboratory studies, and field studies.

Several specific objectives were addressed while seeking to address the overall goal.

Specifically, this work sought to:

- 1) Determine which chemical and physical properties of fuels limit/control ignition and emissions of smoldering combustion.
- 2) Discover what causes changes in ignition and emissions as the fuel density, shape, and moisture content are changed.
- 3) Discover why smoldering changes for different modes of heat transfer.
- 4) Evaluate which processes control burn duration and propagation rate of smoldering.
- 5) Measure field conditions and combustion performance to anchor and validate models.
- 6) Develop relationships between gaseous emissions (e.g., CO₂, CO, CH₄), volatile organic compounds (VOC), fine particulate matter PM_{2.5} (particles < 2.5 µm), and temperature and heat flux for smoldering combustion.

Our first working hypothesis was that differences in smoldering ignition reported for various fuels, moisture contents, and fuel conditions are controlled by common limiting physical or chemical processes (e.g., reaction rates of cellulose, hemicellulose, and lignin). Our second working hypothesis was that key processes that control ignition also control smoldering propagation and influence pollutant emissions. The results from this work did not prove either hypothesis, however — the results we obtained continue to support both hypotheses.

1.3 Technical Approach

Laboratory, field, and modeling studies were used to help achieve the overall goal of this project of determining physical and chemical processes that control smoldering ignition, propagation, and emissions. Laboratory efforts were used to systematically isolate effects on smoldering caused by changes in fuel composition, fuel characteristics (e.g., density or particle size), and boundary conditions (e.g., wind). Data collected during laboratory studies were used to validate numerical studies. Both horizontal and vertical smoldering were considered. Computational efforts focused on enhancing and applying a one-dimensional model for analyzing and identifying key processes influencing smoldering ignition and propagation rates. The model was used to help elucidate key physical and chemical processes causing the experimental observations. Field studies, and samples collected from the field and burned in the laboratory, were used to evaluate scaling effects, and help understand the applicability of results from the other experiments to field conditions. Emissions data was collected from field samples to better understand the sensitivity of emissions to fuel conditions.

Experimental efforts consisted of studies to identify the horizontal smoldering behavior, downward propagation rates, and smoldering characteristics of field samples. In general, the experimental studies consisted of a reactor box where the fuel is burned, an infrared (IR) camera to track horizontal smoldering propagation, and a stainless-steel mirror to reflect images to the camera. The reactor box was composed of 1.3cm-thick calcium silicate insulation board and was roughly 20cm by 20cm by 5cm deep. The IR camera recorded top-down images reflected off of a mirror 1m from the camera horizontally and 0.75m above the fuel. Thermocouples imbedded in the fuel bed were used to determine the downward smoldering behavior for some tests.

The fuel was ignited using a 20W cartridge heater placed at the surface in the center of the reactor for most tests. Any fuel that adhered to the heater was scraped back into the middle of the

reactor box. The burns typically lasted for 1–3 hours. The horizontal propagation velocities were determined from changes in the location of the smoldering front based on infrared images. The burned area for each image is measured from the number of pixels above the threshold of photon counts corresponding to when the smoldering front would self-sustain (near 1800 counts). The burned area was assumed to be circular (except for smoldering of natural samples), and the radius was obtained from the burned area. Downward propagation rates, were determined from temperature measurements recorded using thermocouples spaced 1 cm apart with the tips of the thermocouples placed in the middle of the box.

With regards to fuels evaluated, extensive tests were conducted with mixtures of cellulose, hemicellulose, and lignin. These fuels were selected because most organic materials consist primarily of these constituents. In turn, the efficacy of developing surrogates to replicate the composition of natural fuels (i.e., Douglas-fir and wheat straw) were evaluated. Douglas-fir wood pellets were burned for some tests. The pellets were processed to change particle sizes. The ranges of the diameter of the particles that were evaluated were $3.18 \text{ mm} > d > 2.12 \text{ mm}$, $2.12 \text{ mm} > d > 1.27 \text{ mm}$, $1.27 \text{ mm} > d > 0.85 \text{ mm}$, $0.85 \text{ mm} > d > 0.51 \text{ mm}$ and $d < 0.51 \text{ mm}$. Finally, a series of experiments were conducted where duff was collected underneath ponderosa pine and Douglas-fir trees and burned in the laboratory.

Emissions measurements were taken of smoldering duff in laboratory and field studies. The field studies isolated a duff sample within the forest which allowed for smoldering to be monitored in its natural environment. The approach to the emissions sampling was to measure the rate of carbon emissions per unit area. This was accomplished by collecting emissions in canisters and then analyzing the canisters at the laboratory. The concentrations of methane, carbon dioxide (CO_2), carbon monoxide (CO), and non-methane hydrocarbons (NMHC) were determined by gas chromatography following EPA method TO-14A (U.S. EPA 1999) with an Agilent model 7890 gas chromatograph equipped with dual flame ionization detectors.

A one-dimensional reactive porous media model was developed using the open-source software Gpyro [28]. The model was used to simulate smoldering of multiple woody and biomass fuels relevant to wildland fire. Gpyro solves one-dimensional transient equations for condensed and gas-phase mass and species conservation, as well as condensed-phase energy and gas-phase momentum equations, and the ideal gas equation of state. In this model, the condensed and the gas phase are assumed to be in thermal equilibrium, and Gpyro takes the shrinkage of the sample during the smoldering process into consideration. The Schmidt number is taken as unity. All simulations were run with an initial time-step size of 0.05 s and cell size of 10^{-4} m , selected after some analysis to keep a balance between accuracy and simulation time [29].

All of our computational studies used a one-dimensional domain, intended to simulate downward propagation of smoldering. The top surface of the domain was modeled as being open to atmosphere, allowing both convection and mass transfer. The bottom surface was set as insulated, but with some small heat transfer to account for losses (via a heat transfer coefficient of $3 \text{ W/m}^2\text{K}$). Most simulations used a moisture content of 10%, to account for the moisture present in natural fuels and that absorbed from the atmosphere. In addition, in some cases we specifically varied the moisture content. Moisture content was considered via a drying step in the reaction scheme. The two main parameters of interest are mean propagation speed of smoldering and mean peak temperature. Propagation speeds were numerically computed by determining derivative of depth with respect to time of peak temperature; in other words, the difference

between two depths divided by the times when those depths reach their maximum temperature. A 1 cm depth interval was used for all cases. The mean peak temperature was calculated similarly by averaging the peak temperatures every 1 cm.

1.4 Results and Discussion

Surrogate fuels composed of hemicellulose, cellulose, and lignin were burned and compared to natural fuels with similar compositions. The results suggest that surrogate fuels can be used to mimic the burning behavior of natural fuels to a reasonable degree of accuracy, for some conditions and fuels. Additional evaluation of the use of surrogate fuels for smoldering burns is needed.

Corresponding experiments and analysis were performed to identify smoldering behavior of real fuels, specifically duff samples collected underneath Douglas-fir and ponderosa pine trees. These two fuels are native and significant to much of the western United States of America. Note that the duff samples were collected in regions that are more arid (i.e., ponderosa pine) or moister (i.e., Douglas-fir) and have relatively different thicknesses and compositions. The smoldering results from burning duff samples are expected to be applicable to a variety of natural fuels as a result of burning samples that have quite different properties. The results from these studies help to bridge the results from the well-controlled laboratory and numerical studies to realistic fuels.

Particulate and gaseous emissions data was collected from the duff samples and correlated to the burning behavior. Measurements of emission characteristics and fluxes is important for ultimately better predicting environmental impacts of smoldering burns.

Specific conclusions from this work are now reported along with representative figures supporting the conclusions.

Influence of Cellulose and Hemicellulose Content

1. When density is fixed, propagation velocities increase with decreasing cellulose content, as shown Figure 1.4.1. This sensitivity is caused by the earlier pyrolysis and higher temperatures that occur when hemicellulose is present in the fuel. When the fuel is loosely packed and the density is not controlled, horizontal propagation velocities increase with cellulose. This is due to the lower densities with higher cellulose contents.

2. For downward propagation, the greatest change in smoldering speed occurs when decreasing the cellulose content from 100% to 85%, but there is relatively little change between 85% and 50% cellulose. This behavior illustrates a non-linear connection between smoldering behavior and the composition of the fuel.

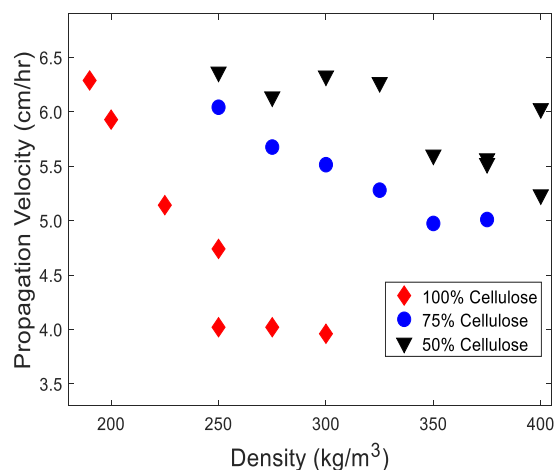


Figure 1.4.1 Horizontal propagation velocities with varying density for three fuel contents. Each data point is for one test. The residual fuel is hemicellulose.

Influence of Lignin Content

3. Fuels with higher lignin content smolder at slower horizontal and vertical propagation speeds. This behavior is caused by the slower pyrolysis and higher activation energy of lignin. Figure 1.4.2 shows the propagation velocity of smoldering fronts in mixtures of cellulose/hemicellulose/lignin. Note that the slowest propagation velocities occur for mixtures with the largest concentration of lignin.

4. As the lignin content increases, the impact of the relative amount of hemicellulose and cellulose decreases. Once the fuel is composed of 20-30% lignin, lignin is the dominant chemical component in influencing smoldering propagation behavior due to its slower reaction rates.

5. Once a minimum concentration of hemicellulose is present in the fuel, additional hemicellulose does not increase the propagation velocity for mixtures of lignin, hemicellulose, and cellulose. This observation is consistent with trends for binary mixtures of cellulose and hemicellulose. The earlier pyrolysis and oxidation in hemicellulose helps spur the reactions, but there are diminishing returns with sufficient concentration of lignin.

6. The minimum radiant heat flux and exposure time required for smoldering ignition depends on fuel composition and can vary by up to 25% (from 7–8.8 kW/m²). This variation comes from the activation energy of the fuel oxidation reactions, which is lower for cellulose than lignin and hemicellulose.

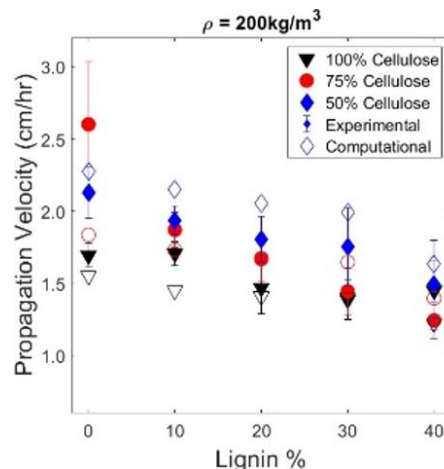
7. Peak temperatures decrease with increasing lignin content in experiments. These results are in contrast to computational results. It is hypothesized that heat losses associated with the longer time required for lignin to burn counteract the potential higher temperatures observed computationally from higher char yield and heat of combustion of lignin. This observation underscores the importance of correctly modeling heat losses.

8. Fuels with lignin derived from pine had faster propagation velocities because of earlier pyrolysis and oxidation compared to lignin derived from tobacco. This indicates that the source of the lignin used in experiments can have an impact on smoldering behavior and may need to be considered when considering the lignin in different natural fuels.

The Efficacy of using Surrogate Fuels

9. Burning of surrogate fuels composed of lignin, hemicellulose, and cellulose can reasonably match the horizontal propagation velocities of ground Douglas-fir and wheat straw. However, downward propagation velocities are only similar when the inorganic content is minimal. Greater inorganic contents in the natural and surrogate fuels cause greater differences in smoldering propagation rates. The differences in downward smoldering in the higher inorganic content cases may be due to differences in ash layer development.

Influence of Density and Moisture Content



1.4.2 Experimental and computational downward smoldering propagation velocities with varying wood smoldering propagation velocities with varying lignin content at density of 200 kg/m³.

10. The expansion of fuels caused by moisture causes the propagation speed of smoldering to increase, due to the reduction in density. If the fuel does not expand with the addition of water (i.e., water fills the fuel pores), propagation speeds decrease due to increase in wet bulk density. In both cases, additional moisture content reduces the mean peak temperature. These results are captured in Figure 1.4.3.

11. The critical moisture content of ignition and extinction is mostly insensitive to fuel composition, except for fuels with higher amounts of hemicellulose. When sufficient hemicellulose is present, the increased heat release and elevated peak temperature allow sustained smoldering, even at higher moisture contents. Thus, fuels with higher hemicellulose contents can ignite—and remain smoldering—at higher concentrations of moisture.

12. For mixtures of cellulose and hemicellulose, horizontal and downward propagation velocities decrease with increasing density. Fuels with hemicellulose demonstrate less of a change in horizontal spread with rising density than pure cellulose. These trends associated with density are attributed to the larger amount of fuel to burn and changes in oxygen diffusion.

13. Adhesion of the fuel and subsequent cracks that can form while burning can have a notable impact (i.e., reduction) on horizontal smoldering spread. The reduction in propagation rates occurs because the dominant mode of heat transfer becomes radiation heat transfer at the crack interface, whereas both conduction and radiation facilitate heat transfer for continuous fuels. It is expected that models will over predict smoldering propagation rates if the physics of cracks in the fuel beds are not captured.

14. The experimental results indicate that reductions in horizontal propagation rates associated with increasing moisture content are caused, in part, because of cracks in the fuel that form. This is suggested by a greater reduction in horizontal propagation rates than downward propagation rates as the moisture content is increased. Cracks can form in the fuel (due to adhesion of the fuel) while smoldering burns spread horizontally, but no such cracks are observed for downward smoldering burns.

Influence of Particle Size on Smoldering Behavior

15. Smaller particles are more prone to self-sustained smoldering and have higher surface and downward smoldering spread rates in porous beds with homogenous particle sizes. The results from these experiments are shown in Figure 1.4.4. Limits on self-sustained smoldering based on particles being sufficiently small are not evident, at least within the ranges evaluated in this study (i.e., $d > 0.5$ mm). The sensitivity of smoldering behavior to particle size is independent of the ignition temperature or heating rate.

16. For fuel beds with mixed particle sizes, relatively larger particles can smolder along the surface if smaller particles are present in the voids. Such physical characteristics are expected for

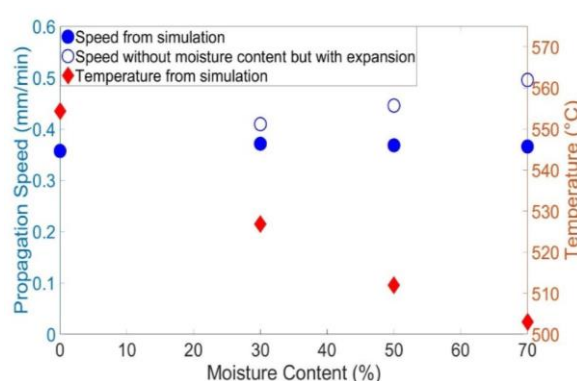


Figure 1.4.3 Propagation speed and mean peak temperature for varying moisture content along with propagation speed with expansion but without moisture content 100% cellulose.

duff. Increasing the particle size requires a larger percentage (by mass) of smaller diameter particles to sustain self-sustained smoldering. Smaller particles facilitate heat being transferred from the reaction zone to virgin fuel.

Effect of Wind on Smoldering Behavior

17. Smoldering spread rates increase when wind speed does. The spread rate at 1 m/s is double the spread rate seen in the same fuel under windless conditions. The increase is attributed to increased oxygen availability and the transport of hot combustion products. Smoldering temperatures increase with wind speed.

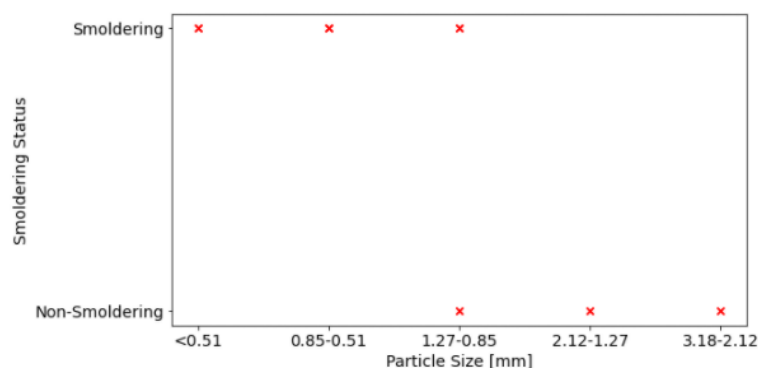


Figure 1.4.4 Particle sizes that resulted in sustained smoldering or no smoldering.

Emissions from Smoldering Burns

20. Physical properties of duff and peat soils, in particular moisture content, packing density, and mineral content, have been identified as important factors affecting the ignition and propagation of smoldering combustion. A primary objective of this project's emissions component was to determine which chemical and physical properties of fuels limit/control emissions from smoldering combustion. A total of eight laboratory burns were conducted. Unfortunately, eight burns were insufficient to determine the impact of duff properties (moisture content, packing density) on emissions from smoldering combustion due to the high natural variability in duff samples and emissions.

21. A key project objective was to develop relationships between emissions, emission factors (EF) and emission fluxes (EM), and smoldering behavior. Measurements of combustion efficiency and emission factors for various burns are shown in Figure 1.4.5. The project focused on smoldering front spread rate and surface temperature as possible drivers of emissions. We found that EF for CH₄, NMHC, and PM_{2.5} increased with increasing surface temperature and spread rate. However, with respect to EM, the only significant relationship observed was a muted positive correlation of EMCH₄ and EMNMHC with spread rate. A multivariate analysis including spread rate and surface temperature and duff physical properties is being pursued to develop predictive smoldering emission models.

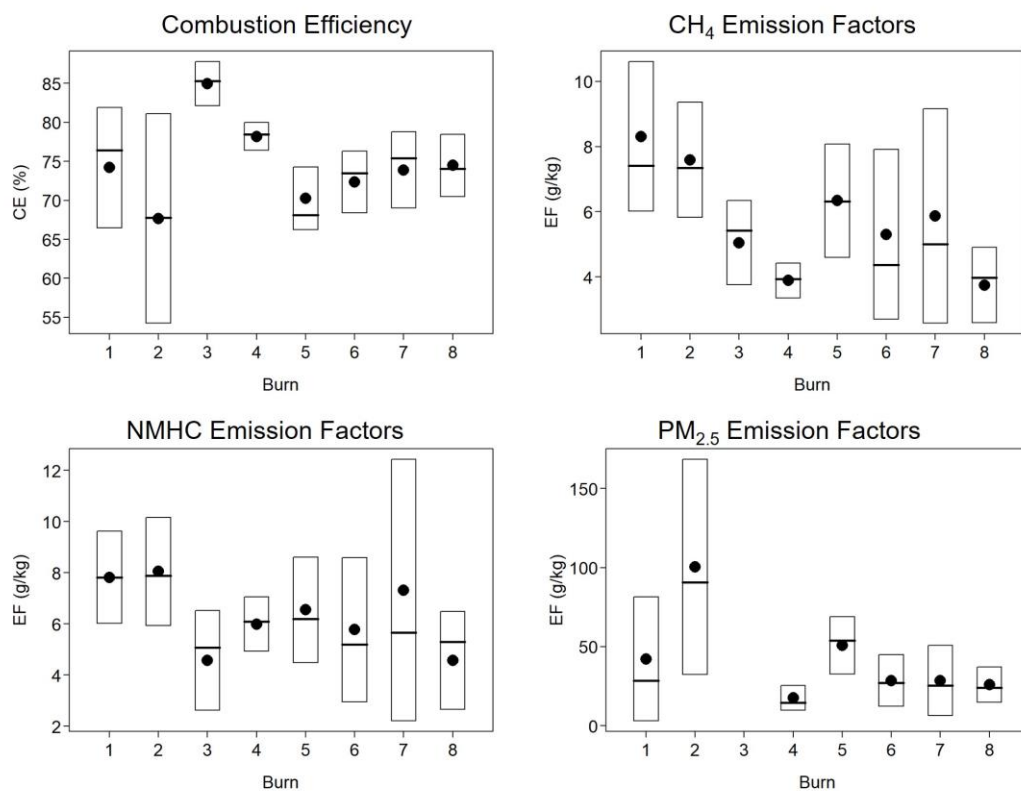


Figure 1.4.5. Laboratory study combustion efficiency (%) and CH₄, NMHC, and PM_{2.5} emission factors (g kg⁻¹) by burn. Circles and horizontal lines are mean and median values and boxes are ± 1 standard deviation.

1.5 Implications for Future Research and Benefits

In summary, this project focused on systematically evaluating how the chemical composition (e.g., cellulose or lignin content) and physical characteristics of the fuel bed (e.g., particle size, moisture content) collectively influence smoldering behavior. Historically, most studies related to smoldering have focused on understanding the smoldering behavior of specific fuels and conditions. A limitation with this approach is that it can be challenging to understand how to apply the knowledge to new conditions (e.g., different densities) or new fuels. However, by systematically considering individual factors that influence smoldering behavior, it is expected that smoldering behavior can be predicted, with reasonable accuracy, even for fuels that have not been burned.

Five implications and benefits of the research are now highlighted. The first major implication from our work is strong evidence that fire managers could be overestimating PM_{2.5} emissions from smoldering burns of duff and, as a result, unnecessarily limiting much needed use of prescribed fire. Laboratory burns were used to measure emission factors (EF) for CO₂, CO, CH₄, PM_{2.5} and 22 NMHC for Douglas-fir forest duff. Douglas-fir duff serves as a proxy for duff found in many forest types present at DoD facilities. Currently, the EF used for smoldering duff and peat in two widely used smoke production models, FOFEM and CONSUME, are MCE-based extrapolations of EF measured for non-duff/peat fuels. For example, FOFEM uses $EF_{PM_{2.5}} = 40 \text{ g kg}^{-1}$ for smoldering western conifer duff. Our study finds the true value of $EF_{PM_{2.5}}$ is closer to 26 g kg^{-1} , indicating fire managers may have been overestimating PM_{2.5} emissions for these conditions. The emission factors quantified in this study will enable more accurate prediction of pollutant emissions from smoldering duff in prescribed fires on DoD lands and fires in western conifer forests.

The second implication of this study is that a new conceptual framework for considering the smoldering behavior of natural fuels has been established. This shift in considering smoldering behavior has the potential to be transformative. Historically, smoldering studies have tended to focus on obtaining and analyzing results from smoldering burns of a specific fuel (e.g., peat) accounting for a specific range of bed conditions (e.g., moisture content or density). Hence, the results and understanding tend to be very specific. This can be problematic when seeking to understand how to apply knowledge from studies to new fuels or new conditions (e.g., different ranges of moisture content, packing densities, etc.). The situation is further complicated when recognizing that hundreds if not thousands of different fuels and fuel conditions exist in nature, and an ability to predict smoldering behavior is needed. In this work the fuels were considered as their fundamental constituents (i.e., cellulose, hemicellulose, and lignin) and physical characteristics (e.g., density, particle sizes). This approach has allowed new insights into smoldering behavior such as the role of lignin in affecting ignition and burning behavior, or how the size of particles changes smoldering propagation rates. As a result of considering the influence of individual aspects of the fuels, knowledge gained from this study can be applicable to a wider range of fuels and conditions encountered in nature. Hence, we expect that knowledge gained from this work can be applicable to many fuels of interest to the DoD.

The third implication is a general model for smoldering has been refined to better inform the impact of composition, moisture content, and density on smoldering ignition and behavior. This model will be openly available and described in detail in publications resulting from the project, and can be used by the community to examine smoldering of particular fuels based on

composition. This is in contrast to using a model validated for a specific fuel. In addition, we extracted simple empirical models for smoldering ignition, temperature, and propagation speed as functions of composition that can be used by practitioners to quickly estimate smoldering-related risks.

A fourth major impact of this work was pioneering the use of surrogate fuels to emulate key characteristics of natural fuels. Prior works have considered surrogate fuels for other complicated fuels (e.g., jet fuels, diesel [30–32]), yet the use of surrogate fuels to understand and predict smoldering combustion has not been widely considered. A surrogate fuel is a simplified fuel that emulates key features of (typically more complicated) natural materials (e.g., burning rate, peak temperatures). An advantage of using surrogate fuels is calculations are more tractable and arguably can better capture key physical and chemical processes. Equally important, the use of surrogate fuels has the potential to allow smoldering behavior to be predicted *a priori* if the constituents and properties of the fuel bed are known.

The fifth major benefit of this project is further understanding the role of heat transfer in controlling/influencing smoldering behavior. We believe that the critical role of heat transfer in controlling smoldering behavior has not been thoroughly appreciated. As noted earlier, experiments were systematically performed where fuels of differing particle sizes were burned. We expected that larger particles would smolder more quickly because of the greater oxygen availability (in the pores between particles). In contrast, reducing the size of particles resulted in faster horizontal propagation rates despite having more fuel to burn within a volume and presumably reduced oxygen availability between the particles. Heat transfer analysis showed that smaller particles more readily transfer heat between particles whereas larger particles can be more sensitive to losses caused by natural convection. We expect that this new fundamental insight will be used by the smoldering community to greatly enhance how we explain and understand smoldering.

2. Objectives

2.1 Objectives

The overall goal of this effort was to obtain the scientific understanding needed to develop tools for assessing risks of ignition, spread, and emissions from smoldering combustion for fuels and conditions applicable to the DoD. Note that the focus was on developing the knowledge, not the tools themselves, although several models were developed/refined as part of this work. To accomplish the overall goal, this work focused on identifying physical and chemical processes that control smoldering combustion through modeling, laboratory studies, and field studies.

Several specific objectives were addressed, at least in part, while seeking to address the overall goal:

- 1) Determine which chemical and physical properties of fuels limit/control ignition and emissions of smoldering combustion.
- 2) Discover what causes changes in ignition and emissions as the fuel density, shape, and moisture content are changed.
- 3) Discover why smoldering changes for different modes of heat transfer.
- 4) Evaluate which processes control burn duration and propagation rate of smoldering.
- 5) Measure field conditions and combustion performance to anchor and validate models.
- 6) Develop relationships between gaseous emissions (e.g., CO₂, CO, CH₄), volatile organic compounds (VOC), fine particulate matter PM_{2.5} (particles < 2.5 μm), and temperature and heat flux for smoldering combustion.
- 7) Assess the influence of physical scale on ignition and propagation characteristics of smoldering.

Technical questions that were partially or completely answered during this project include:

- 1) What are chemical processes that control ignition of smoldering combustion for fine fuels?
- 2) How does the physical condition of the fuel (e.g., packing density, shape, moisture content) alter smoldering behavior?
- 3) How does the size of fuel particles influence and/or limit propagation rates of smoldering combustion?
- 4) What causes smoldering spread dominated by conduction to differ from that of radiative heat transfer?
- 5) What are the rates of pollutant emission from smoldering burns and how are the rates influenced by the fuel composition?

2.2 Hypotheses

- 1) Our first working hypothesis was that differences in smoldering ignition reported for various fuels, moisture contents, and fuel conditions are controlled by common limiting physical or chemical processes (e.g., reaction rates of cellulose, hemicellulose, and lignin).
- 2) Our second working hypothesis was that key processes that control ignition also control smoldering propagation and influence pollutant emissions.

While the results from this work did not prove either hypothesis, the results we obtained continue to support both hypotheses.

3. Background

3.1 Motivation

Managing impacts of smoldering combustion during wildland fires is critical to supporting Department of Defense (DoD) missions.

Smoldering combustion is significant because it can damage ecosystems, contribute substantially to air pollution and carbon emissions [1–5], affect public health, and transition to

flaming combustion [5–7]. A challenge associated with smoldering combustion is that it can affect both the immediate ecosystem and surrounding regions. In the immediate vicinity, the air, soil, and fauna can be drastically altered because of the high temperatures and removal of litter and duff near the ground. In extreme cases, smoldering can contribute to the mortality of mature or old-growth trees [8]. In the regions surrounding a smoldering burn, severe air pollution can occur as smoldering releases more carbon monoxide (CO), methane (CH₄), volatile organic compounds (VOC), and fine particulate matter (PM_{2.5}) on a per mass basis than flaming combustion [2, 9]. The environmental impact on the surroundings is further complicated because the smoke produced by smoldering often remains near the surface and disperses slowly in the absence of a convective plume from an adjacent flame front. As a result of the high pollutant production rates and poor dispersion conditions, smoldering combustion frequently impacts adjacent communities by affecting air quality, visibility, and public health [10].

Fire modelling tools that consider ignition, propagation, and pollutant emission characteristics from smoldering combustion are essential to enable informed fire-management decisions. However, current tools for predicting the ignition of smoldering combustion [11–13], as well as the burn duration [11, 14, 15] and its impacts on air quality [9, 16, 17] and soil productivity, are severely limited. This hindrance results from limited knowledge about the controlling processes in smoldering combustion. Prior research has often obtained empirical trends or results specific to a fuel type, such as peat [9, 18–20] or cotton [7, 21], and condition. What is needed are discoveries about the physical and chemical processes that control ignition, propagation, and pollutant emissions of smoldering combustion for all fuel conditions. Such discoveries can enable the development of advanced predictive fire modelling tools.

3.2 Background: Understanding and Knowledge Gaps Leading to Research

The physical and chemical processes that control ignition, propagation and emissions can be categorized into: fuel characteristics, scaling, and thermal and mass transport, as illustrated in Figure 3.1.1. Smoldering studies have typically investigated aspects of these key processes, but typically only for specific fuels or conditions [9, 11–13, 16, 17, 22–24] [9, 11–13, 16, 17, 22–24] [9, 11–13, 16, 17, 22–24]. As a result, it is not possible to predict a priori if smoldering ignition or propagation will occur outside of the conditions that were investigated. Parameters that control ignition are not fundamentally well understood and rate limiting parameters are still unknown. For example, recent computations and experiments regarding smoldering combustion of peat provided valuable understanding about the effect of moisture content and what concentrations limit propagation [19, 25–27]; yet, it was not clear how those findings extend to other fuels, including those significant to DoD. The remainder of Section 3.2 summarizes

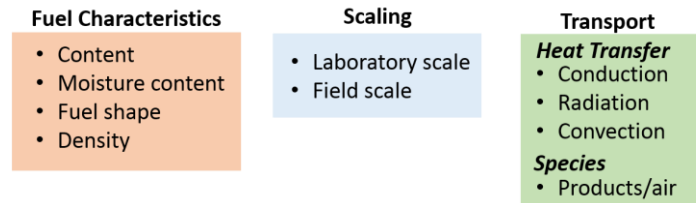


Figure 4. Copy and paste and using Figure 1 to label. Parameters that can affect smoldering ignition,

knowledge about smoldering ignition, propagation and emissions to understand what physical and chemical processes need to be investigated.

3.2.1 Smoldering Combustion Ignition and Propagation

The process of smoldering ignition and propagation is illustrated in Figure 3.2.1.

Initially, a heat flux is applied to organic material(s). The heat flux raises the temperature of the organic matter and causes pyrolysis [33]. The volatile pyrolysis components diffuse or

advent away from the surface [34]. Oxidation reactions occur with the residual solid material if enough oxygen is present and temperatures are high enough for reactions. To be self-sustaining and propagate, heat released from the reactions must be sufficient to raise the temperature of surrounding material and maintain pyrolysis and oxidation. Unlike flaming combustion, the oxidation reactions controlling smoldering combustion occur in the solid phase instead of the gas phase [14]. This makes smoldering combustion much more sensitive to the solid properties and oxygen transport to the surface. Smoldering combustion can be limited by diffusion of oxygen to the reaction zone [20, 35, 36].

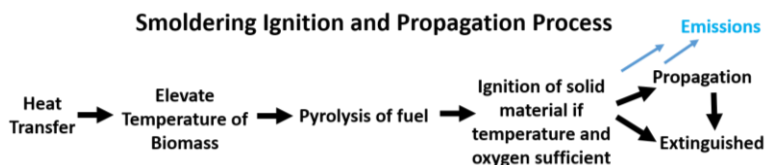


Figure 3.2.1: Process for smoldering combustion ignition and propagation.

Material composition and shape can have a significant effect on ignition and propagation of smoldering combustion [37–40], but the physics controlling this sensitivity are not well understood. For example, differences in ignition have been noted when hot objects are placed in contact with different organic materials. Natural fuels tend to be more difficult to ignite than cellulose powder (i.e., surrogate fuel). It was suggested, but needs to be verified, that the difference in sensitivity results from the shapes of the organic material and the presence of other materials, such as lignin [41]. Other work has shown that the threshold for smoldering combustion of peat depends on its decomposition kinetics, inorganic content, and moisture content, among other parameters [5, 25]. Similar understanding is needed for a range of fuels applicable to the DoD. This can be accomplished by discovering the rate limiting diffusion or chemical kinetic processes that control ignition or propagation for different fuels. With this knowledge, the susceptibility of materials to smoldering could be determined based on the composition, instead of requiring testing for all potential fuels.

The literature also notes a sensitivity of smoldering combustion to material density [42]. Hagen and coworkers [7] found that, in smoldering propagation of cotton, samples with relatively high density transitioned to flaming combustion while lower densities remained in smoldering mode. This was attributed to differences in the location of the smoldering and secondary char oxidation. Rein [5] noted that thicker piles of fuels tend to be more prone to smoldering combustion than thinner. It is not understood if the sensitivity to density occurs because of differences in the heat transfer, changes in the reaction rate because of differences in reactant concentrations, or both.

3.2.2 Role of Heat Transfer

Three modes of heat transfer are possible for igniting smoldering combustion: conduction from hot objects (e.g., pieces of ordnance, embers), radiative heat fluxes, or convection from hot combustion products. All three modes can be significant to ignition [34, 37–41]. Ignition from

conduction can occur when hot objects are in contact with organic material. This mode of ignition is sensitive to the temperature, size, and composition of the hot object. Despite this type of understanding for specific fuels, the ability to model ignition from conduction is quite limited, as suggested by the discrepancy observed between theoretical and measured results [41]. Moreover, it is not clear how to relate results to other fuels or conditions. This challenge results from complications associated with the coupling that occurs between heat transfer, pyrolysis, and oxidation.

Ignition due to a radiative heat flux is sensitive to how the flux is applied. For example, smaller sample sizes of polyurethane require larger critical radiant heat fluxes to ignite than larger samples. Moreover, radiative ignition of smoldering tends to be more sensitive to the sample size than flaming [43]. Our theory is that this sensitivity results from changes in heat losses. Interestingly, it has been observed that a cycled heat flux (e.g., flame flapping) requires a lower material temperature for ignition than when a constant heat flux is applied [21]. This further alludes to a link between the rate of temperature rise and chemical kinetics that needs to be investigated.

Convective heat transfer can have a significant influence on propagation and ignition of smoldering combustion [13, 38, 44, 45]. In computational studies of porous polyurethane foam, the smoldering combustion velocity was controlled by the oxygen concentration at the reaction zone. At higher convective speeds the smoldering combustion velocity is controlled by chemical kinetics [42] while excessive velocities can also cool the reaction zone [46]. In coupled radiative and convective heat transfer to wood, increasing the velocity of the surrounding air tends to delay ignition while increasing the temperature of the air changes surface heating prior to ignition [47]. This overview of the literature highlights the fact that studies considering convection have typically been for specific fuels.

3.2.3 Physics-based Models

Models capturing key physics can provide guidance when determining the most important parameters (e.g., density, moisture content, composition) governing ignition, propagation, and emissions from smoldering combustion. Such models work by solving equations for physical conservation laws (e.g., mass, momentum, energy) to determine the evolution of variables including temperature, pressure, and species mass fractions [28]. In addition, heterogeneous chemical reactions are considered to model the pyrolysis—i.e., chemical decomposition due to heating—of the solid combustible material followed by the oxidization of the resulting solid char [48]. Since these models explicitly represent thermodynamic, physical, and chemical properties of materials, key physical or chemical processes can be determined that limit smoldering combustion. Moreover, it can be determined whether or not these factors are universal for different fuels and conditions. Existing computational studies for smoldering combustion typically use one-dimensional models and neglect the contribution of gas-phase chemical reactions due to their perceived lesser role [14, 25, 48, 49].

Huang et al. [25] developed a one-dimensional physics-based model for smoldering peat combustion. While the model considered the mass fractions of four gaseous species, no gas-phase chemical reactions were simulated. In the study, ignition was achieved by application of a simple heat flux. Their results showed that the threshold for smoldering combustion of peat depended on decomposition kinetics, physical properties, and the ignition protocol. However, the key chemical properties of the decomposition kinetics were not studied further, and the

ignition protocol was only varied in terms of the heat flux value. Additional study is required to determine how different sources of ignition and organic material affect smoldering combustion, and understand the role that different chemical and physical properties play. Existing computational models used for smoldering combustion are not capable of simulating these more complex ignition sources.

A working hypothesis related to the chemical kinetics of smoldering combustion is that different fuels may break down into common intermediate species. This concept is similar to an approach recently proposed for formulating surrogate jet fuels [30, 31], where gas-phase combustion behavior is primarily determined by the ability of various fuels to form a “radical pool” of important species. The differences in fuel chemistry, therefore, mainly contribute to varying size and makeup of this radical pool, which then results in different overall combustion behavior.

The level of detail in chemical kinetics considered for smoldering combustion in the literature is limited. As mentioned above, previous efforts studying the ignition of smoldering combustion neglected gas-phase chemistry; therefore, the current state-of-the-art model is unable to predict or study the chemical kinetics involved in convection of hot combustion products. Furthermore, Ohlemiller [14] suggested that gas-phase oxidation may play a significant supplementary role in smoldering ignition and wave propagation. Similarly, Lautenberger and Fernandez-Pello [50] recently indicated that gas-phase reactions may contribute to overall heat release in the case of oxidative pyrolysis. It is expected that gas-phase reactions will contribute significantly to the emissions of smoldering combustion.

Prior computational studies of smoldering combustion used chemical kinetic models of limited complexity, including one- [51], three- [14], and five-step [25, 52] chemical kinetics. A more complex model with six reaction steps and 11 species (both condensed and gas-phase) was used to study oxidative pyrolysis of wood. Notably products from char oxidation and pyrolysis are lumped into single species. In reality, these groups can include important gaseous species such as CO, CO₂, CH₄, and other volatile compounds and unburned hydrocarbons. Detailed studies of the role chemical kinetics plays in the ignition, propagation, and emissions of smoldering combustion require using models that better capture the chemistry than prior efforts.

3.2.4 Emissions from Smoldering Combustion

The production and composition of wildland fire smoke depends heavily on the ratio of flaming to smoldering combustion. Smoldering combustion produces the regulated criteria air pollutants CO and PM_{2.5} as well as numerous VOCs. In addition to being pollutants in their own right, VOCs can lead to the production of ozone that is another regulated criteria air pollutant. Unfortunately, there is a lack of field and laboratory studies on the relationships between emissions and smoldering combustion conditions that can be incorporated into predictive models. Given the regulatory and public health issues associated with wildland fire smoke, a primary concern of land managers when utilizing prescribed fire is to mitigate smoke impacts by minimizing smoldering combustion. The current inability of land managers to reliably predict the initiation and propagation of smoldering combustion and the associated emissions is a major obstacle to applying fuel treatments.

Pollutant production by fires is predicted through the use of emission factors. Emission factors are defined as the mass of a pollutant emitted per mass of fuel burned. Thus, emissions can be predicted if the consumption rate of fuel is known. The emission factors for PM_{2.5} and many VOCs are correlated with the modified combustion efficiency (MCE), which is the ratio of CO₂

emitted to the sum of emitted CO₂ and CO [53]. Linear relationships between emission factor and MCE are frequently used to predict emissions [53–55]. While MCE is considered a measure of the relative ratio of flaming and smoldering combustion, its relationship to the physical fire process has not been explored. Current emission models, such as CONSUME and FOFEM, predict the mass of fuel consumed in the flaming and smoldering combustion phases and then apply phase specific emission factors to predict pollutant emissions. This approach assumes that emissions from smoldering combustion can be represented with a single MCE. However, it is known that MCE and pollutants produced in smoldering combustion can be highly variable (e.g. [4]).

3.2.5 Scaling Effects of Smoldering Combustion

Smoldering combustion can have critical implications for mortality of existing flora as well as impacts on human activities due to the smoke emissions [9, 56–58]. Smoldering combustion of peat and muck soil plays an important role in the creation and maintenance of wetlands [59]. It has been demonstrated that moisture and mineral content influence smoldering extent. For example, some studies have shown that moisture contents of more than 250% (dry mass basis) can sustain smoldering, yet as moisture contents exceed 260% the probability of sustained burning drops quickly [26, 59, 60].

4. Materials and Methods Used for Research

Laboratory, field, and modeling studies were used to help achieve the overall goal of this project of determining the physical and chemical processes that control smoldering ignition, propagation, and emissions. Our working hypothesis was that ignition, propagation, and pollutant formation are controlled by common processes which, if understood, can ultimately be used to create a predictive tool applicable for many fuels and environmental conditions. Laboratory efforts were used to systematically isolate effects on smoldering caused by changes in fuel composition, fuel characteristics (e.g., density or particle size), and boundary conditions (e.g., wind). Data collected during laboratory studies were used to help validate numerical studies. Both horizontal and vertical smoldering were considered. Computational efforts focused on enhancing and applying a one-dimensional model for analyzing and identifying key processes influencing smoldering ignition and propagation rates. The model was used to help elucidate key physical and chemical processes causing the experimental observations. Field studies, and samples collected from the field and burned in the laboratory, were used to evaluate scaling effects, and to help understand the applicability of results from the other experiments to field conditions. Emissions data was collected from field samples to better understand sensitivities of emissions to fuel conditions.

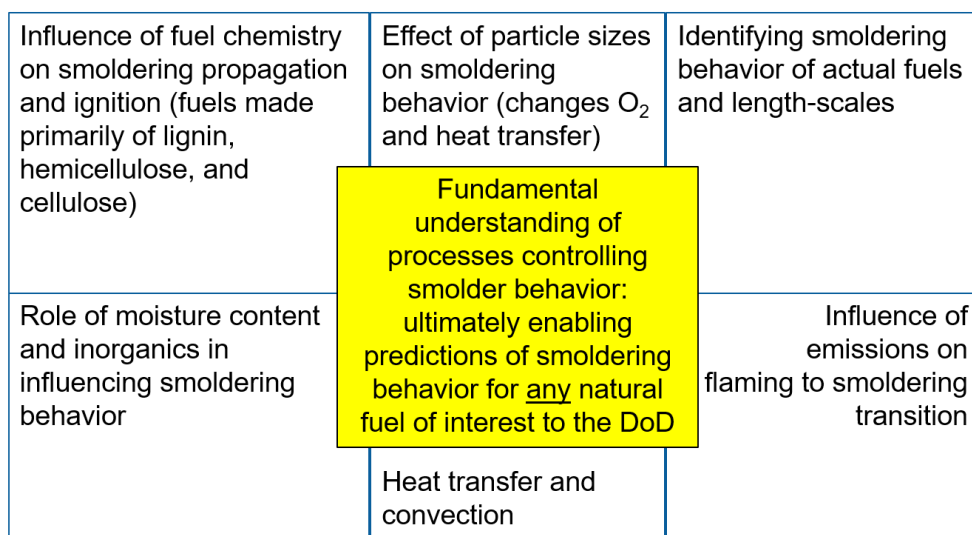


Figure 4.1: Laboratory, field studies and modeling approach for investigating ignition, propagation and emissions from smoldering combustion.

Multiple chemical and physical characteristics influence smoldering behavior, as described in Section 3. To ultimately be able to predict smoldering behavior (e.g., propagation and emissions rates), understanding of at least 6 aspects of smoldering behavior is required, as illustrated in Figure 4.1. In Sections 4 and 5 we detail the methods and results that we used to gain understanding of all 5 of the aspects that can affect smoldering behavior. What was not addressed, and ultimately should be considered, is the influence of gaseous emissions on the transition from flaming to smoldering combustion.

The remainder of Section 4 provides details of the methods used for conducting the laboratory studies, field studies, modelling, and analysis of the gaseous emissions. Table 4.1 maps how the various research approaches were being used to address the objectives of this project.

Table 4.1. Mapping of research approaches being uses to address project objectives.

Objective	Research Approach
1) Identify key chemical and physical properties controlling ignition of smoldering combustion	Computations (Section 4.6)
2) Evaluate processes that control burn duration and propagation	Laboratory experiments (Section 4.1), computations (Section 4.3)
3) Evaluate why smoldering changes for different modes of heat transfer	Analysis of influence of particle size (Section 4.2), Calculations (Section 4.6)
4) Evaluate which processes control burn propagation rates	Laboratory experiments (Section 4.1) Computations (Section 4.6)
5) Measure field conditions and smoldering behavior of field samples	Field studies and burning field samples in laboratory (Section 4.4)
6) Develop relationship between emissions and smoldering behavior	Field studies and burning field samples in laboratory (Section 4.4), Emissions sampling (Section 4.5)
7) Assess physical scale on ignition and propagation characteristics of smoldering	Laboratory experiments evaluating the size of particles (Section 4.2), Field studies and burning field samples in laboratory (Section 4.4)

4.1 Evaluating Influence of Fuel Composition

A series of laboratory experiments were conducted to help identify the influence of fuel composition, particle sizing, and wind speeds on smoldering behavior. Both downward and horizontal smoldering were considered because differences can exist in the controlling physics [23]. Different arrangements were used as needed and as noted. The approaches for studying both smoldering directions are discussed followed by a review of how the fuel characteristics were varied.

4.1.1 Horizontal Smoldering Characteristics

The arrangement for the horizontal smoldering studies is shown in Figure 4.1.1. It consists of a reactor box where the fuel is burned, an infrared (IR) camera to track horizontal smoldering propagation, and a stainless-steel mirror to reflect images to the camera. The reactor box is composed of 1.3 cm thick calcium silicate insulation board and was 20 cm by 20 cm by 5 cm deep. The IR camera (FLIR SC6700) records top-down images reflected off of a mirror. The mirror was placed 1 m from the camera horizontally and 0.75 m above the fuel. The sampling frequency of the camera was 0.1 Hz, and the integration time was 0.48 μ s. The spatial resolution of the camera was about 0.33 mm/pixel.

The fuel was ignited using a 20W cartridge heater placed at the surface in the center of the reactor. For fuels with hemicellulose and cellulose, the temperature of the heater was limited to 550°C. For fuels with lignin, the limit was

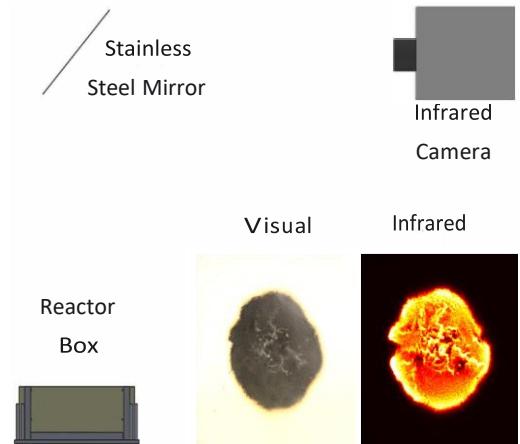


Figure 4.1.1 Experimental arrangement for measuring the horizontal smoldering propagation velocities during smoldering combustion. The visual and infrared images are from the same burn (75% cellulose, $\rho = 200 \text{ kg/m}^3$) approximately 40 minutes after ignition. The burned section is approximately 10 cm across.

650°C as lignin requires a higher ignition temperature. The igniter was placed in the fuel for 3 to 10 minutes depending on when the smoldering was self-sustaining. Any fuel that adhered to the heater was scraped back into the middle of the reactor box. The burns typically lasted from 1–3 hours. The horizontal propagation velocities were determined from changes in the location of the smoldering front based on infrared images. The burned area for each image was measured from the number of pixels above the threshold of photon counts corresponding to when the smoldering front would self-sustain (near 1800 counts). A spatial calibration was used to convert the number of pixels to a surface area. Once the fuel ignited at a given pixel location it was considered to be burned for duration of the burn, even if it cooled after the reaction front passed.

The burned area was assumed to be circular, and the radius was obtained this area. Figure 4.1.1 shows representative visual and infrared images. After a transient period of 10-20 minutes, the change in radius of the smoldering front over time is nearly linear, as shown in Figure 4.1.2. The reported propagation velocity is this linear change in radius with time, so the transient period was not reported. Based on the error in the calibration and linear fit, the bias uncertainty of the mean propagation velocities was estimated near 2%. The precision uncertainties were larger, in the range of 10-20%.

4.1.2 Downward Smoldering Characteristics

Downward propagation velocities were determined by burning samples in a second reactor box, with inside dimensions of 10 cm by 10 cm by 10 cm. The larger distance in the downward direction allows for more accurate smoldering propagation rate measurements because of reduced heat losses through the bottom of the reactor box. Temperatures within the fuels were measured using sheathed type-K thermocouples. The thermocouples were spaced 1 cm apart with the tips of the thermocouples placed in the middle of the box. Temperature measurements are recorded at 1 Hz. The fuel was ignited using the same method as the horizontal smoldering tests. The burns typically last 2-12 hours depending on the composition and density of the fuel. The fuel was considered ignited at a thermocouple location when the temperature reached 300°C. An example of the temperature profiles with time is shown in Figure 4.1.3.

These temperature thresholds are estimated from when heat release occurs in cellulose and hemicellulose in an oxygenated environment using differential scanning calorimetry (DSC), which is approximately 300°C. The propagation velocity is determined by the distance between the thermocouples divided by the difference in time to ignite (i.e., reach 300°C) between the thermocouples. The propagation velocity from 3 to 6 cm below the surface is reported unless stated otherwise. 3 cm was chosen as the starting point because the thermocouples above it were

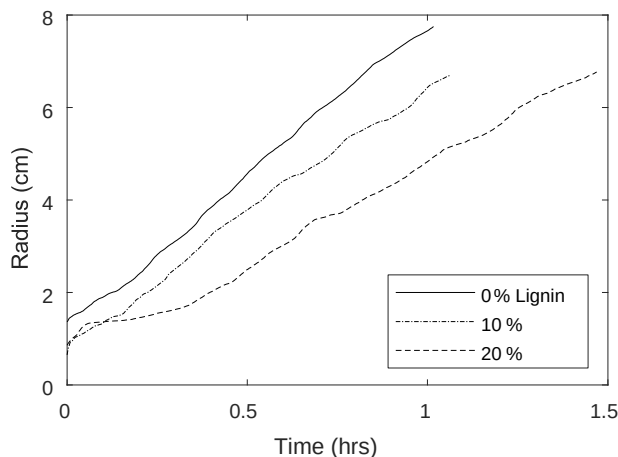


Figure 4.1.2 The radius of the burned area with time for three different tests. The non-lignin portion of the fuel is 75% cellulose (residual hemicellulose), and the density is 300kg/m³. Note the inflection point at about 0.3 hours in the 20% lignin case. This is where it transitioned from transient to steady-state.

more sensitive to how long the igniter was on and how close it was to the exact center of the box. 6 cm was chosen as the ending depth for collecting data to limit impacts from the bottom surface and because of time constraints when testing.

4.1.3 Fuels Evaluated During Downward and Horizontal Smoldering Experiments

Most organic materials consist primarily of cellulose, hemicellulose, and lignin. Hence, a significant effort was applied to understand how these constituents affect both downward and horizontal smoldering behavior. The work culminated in evaluating the efficacy of developing surrogates to replicate the composition of natural fuels containing cellulose, hemicellulose, and lignin. These fuels were considered because these are the three most common organic constituents found in biomass [61]. This phase was broken up into two studies, with the first focusing on just cellulose and hemicellulose mixtures, and the second added lignin with fixed contents of cellulose and hemicellulose. The study with cellulose and hemicellulose has already been published [62], and the lignin study is in the process of being written. The cellulose used in these experiments was α -cellulose (Sigma-Aldrich) because it is the type of cellulose with the least amount of degradation. Glucomman was used for the hemicellulose (Nutricost) because it is one of the more common hemicellulose types and was available in large quantities. An organosolv lignin derived from yellow pine (Attis Innovations) was used for this study after evaluation of 5 sources of lignin. An organosolv lignin was selected over sulfonated lignins because organosolv lignins have a low inorganic content ($<1\%$) and has propagation velocities that are relatively similar to that corresponding to combinations of cellulose and hemicellulose. Among the two organosolv lignins tested, the pine-derived lignin was selected for the experiments over a tobacco-derived lignin because it had more consistent smoldering behavior. Furthermore, because pine is more similar to relevant natural fuels like ponderosa pine and Douglas-fir. The process for selecting the lignin is described in the following subsection.

The selection of lignin is important because the method used to extract the lignin can significantly affect its chemical structure [63, 64]. The structure of the lignin is also impacted by the feedstock it is extracted from. Two classes of lignins were evaluated: sulfonated and organosolv. The former is created by adding an alkali sulfonate to the biomass to make the lignin soluble [63]. The latter lignin is created by using organic solvents to separate lignin from the rest of the biomass [64]. Three sulfonated lignins (Marasperse, Norlig, and Ufoxane) obtained from Borregaard and two organosolv lignins obtained from Attis Innovations were evaluated. The extraction processes can potentially bias the smoldering behavior by increasing inorganic content, adding other contaminants, or degrading the lignin. To detect potential biases, the fuels were first tested to determine their inorganic content. Second, the fuels were burned in

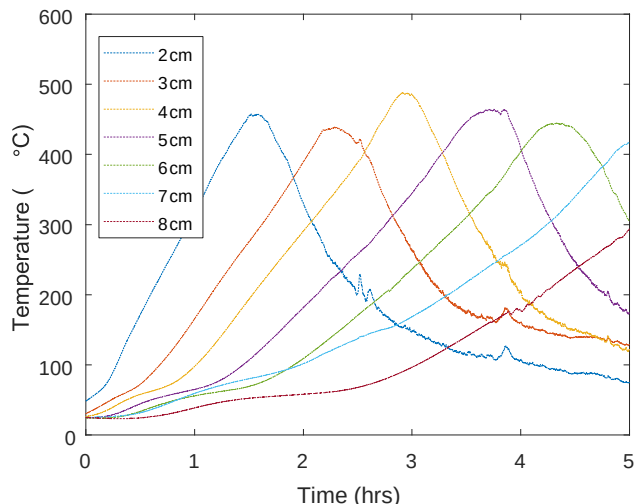


Figure 4.1.3: Temperature profiles for a burn with 100% cellulose at a density of 200kg/m^3 . Each line is the temperature plot at a given thermocouple location. The thermocouples are spaced 1 cm apart from 2 to 8 cm below the surface of the fuel.

combinations of cellulose and hemicellulose to determine if the horizontal propagation velocities were within the range of expected outcomes.

Table 4.1.1 shows the residual inorganic content and horizontal propagation velocities for four of the lignins tested. The organosolv lignin was derived from tobacco (the pine-derived was not tested in this round). The Marasperse and Ufoxane had relatively high inorganic contents (approximately 70% by mass). The Norlig had a lower inorganic content of 18%. The organosolv also had a negligible inorganic content (<1%). For the smoldering tests, each of the lignins composed 20% of the fuel by mass, with cellulose making up 60% and hemicellulose the remaining 20%. The density was 300kg/m³. The horizontal propagation rates for mixtures with Marasperse and Ufoxane respectively were relatively fast (10 and 8.4 cm/hr, respectively). The propagation velocities were significantly lower when the Norlig (3.8 cm/hr) or organosolv lignin (4.5cm/h) was used as the lignin source. For reference, combinations of cellulose and hemicellulose at the same density ranged from about 3.9 cm/hr for 100% cellulose to 6.3 cm/hr for 50% cellulose (and 50% hemicellulose) [62]. It is expected that the smoldering propagation rate would be similar to or less than corresponding tests with cellulose and hemicellulose because lignin has a higher activation energy and higher pyrolysis temperatures than cellulose and hemicellulose [65–67]. Between the faster propagation rates and high inorganic contents, the Marasperse and Ufoxane were deemed unsuitable. While Norlig had more appropriate propagation velocities than Marasperse and Ufoxane, it still had higher inorganic content than the organosolv lignin, so the inorganic content would still change substantially as lignin content changed. Thus, the organosolv lignin was selected.

Table 4.1.1: Horizontal propagation velocities and inorganic content for multiple lignins in mixtures of 20% lignin, 60% cellulose, and 20% hemicellulose. The first three lignins are sulfonated lignins, and the last two are the organosolv lignin.

Lignin Type	Horizontal Propagation (cm/h)	Inorganic Content
Marasperse	10.0	71%
Ufoxane	8.4	66%
Norlig	3.9	18%
Organosolv Lignin	4.5	<1%

In our initial round of lignin testing, we used the tobacco-derived lignin, and the results are shown in Figure 4.1.4. The downward propagation velocities decrease with lignin content for all cases, and fuels with hemicellulose in the non-lignin portion have faster propagation velocities than those with just cellulose. Later, a pine-derived lignin from the same supplier as the tobacco-derived lignin became available for testing. Similar trends are observed with the pine-derived lignin, but the propagation velocities are higher with the pine-derived lignin. Although the sample sizes are relatively small (three tests at each point for tobacco-derived lignin, two tests for pine-derived), statistically there is strong evidence that the pine based lignin burns faster than the tobacco derived lignin, and that the difference is not due to random results ($p < 0.001$, ANOVA).

Ultimately, the pine-derived lignin was selected for this research. The reasons were two-fold. First, it was discovered that some of the tests with the tobacco-derived lignin exhibited a decay in

peak temperatures with depth, indicating that the smoldering front was extinguishing. The peak temperature decay was not observed with the pine lignin, and is also not observed (at least at these depths) in high lignin fuels such as peat [19, 20, 23]. Second, pine is more similar to relevant natural fuels such as ponderosa pine and Douglas-fir.

4.1.4 Fuel Preparation

The percentage of each fuel in the mixture was determined by mass. For the study with cellulose and hemicellulose, the cellulose was varied from 50% to 100%, and the remainder of the fuel was hemicellulose. For the lignin study, the lignin content was systematically varied from 0 to 40% by mass. Admittedly, this range does not cover all lignin contents seen in biomass, as lignin content can be as high 55%. However, the lignin content for most lignocellulose biomass is 10-25% [63]. In the lignin study, the percentage of cellulose and hemicellulose in the remainder (non-lignin portion) of the fuel was held constant during this study to avoid varying the amount of cellulose and hemicellulose independently. The three conditions evaluated for the non-lignin fuel are 100% cellulose, 75% cellulose and 25% hemicellulose, and 50% cellulose and 50% hemicellulose by mass. The uncertainty in fuel content percentage is approximately 0.5% (as an absolute value). The fuels were packed manually to the desired density. The bias uncertainty of the density is approximately 10 kg/m^3 based on the error in the mass of the fuel and the dimensions of the reactor box.

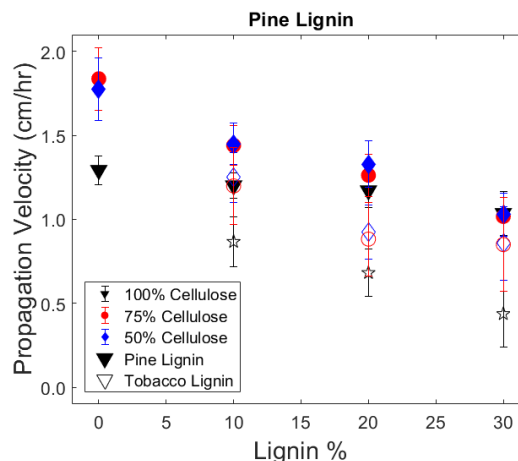


Figure 4.1.4: Measured downward propagation velocities determined at varying lignin contents for two lignin types and three hemicellulose/cellulose combinations.

4.1.5 Evaluation of Smoldering of Surrogate Fuels

The efficacy of using surrogates in smoldering studies was evaluated by comparing the downward and horizontal smoldering propagation rates and peak temperatures for natural fuels and their surrogates. The physical and chemical characteristics of the natural fuels considered for developing the surrogate are organic fuel composition, inorganic content, moisture content, density, and particle size.

The natural fuels used for this study were wheat straw and Douglas-fir. To achieve consistency in size and to help reduce the influence of changes in the sizes of particles, the fuels were obtained as pellets, granulated, then filtered using screens to achieve particle sizes less than 1/20 inch (1.27 mm). For the wheat straw pellets, the fuels were also filtered to be greater than 1/50 inch (0.508 mm) to remove dust particles.

Table 4.1.2 show the approximate values for the lignin content, cellulose, hemicellulose, other organic material, inorganic content, and density. The percentages of cellulose, hemicellulose, lignin, and inorganic content by mass in the Douglas-fir were determined from testing by Waypoint Analytical (total of 3 tests). The chemical composition of wheat straw was obtained from literature [68–70]. The percentages for the organic components are the percentage of all organic material in

the fuel. The density is the total density (i.e., includes inorganic material). The "Other" category is organic material that is not cellulose, hemicellulose, and lignin, such as sugars or proteins [69]. The contribution of these other constituents to these fuels is relatively small, so they are ignored in creating the surrogate mixtures. Further research will be required for fuels with larger amounts of organic material that is not lignin, cellulose, or hemicellulose.

Table 4.1.2: Fuel composition and densities for the natural fuels and surrogates.

Fuel	Lignin	Cellulose	Hemicellulose	Other	IC	Density
Wheat Straw	16-25%	33-49%	22-27%	5-12%	7-11%	220
WS surrogate	20%	47%	33%	N/A	9%	220
Douglas-Fir	24-29%	45-49%	10-14%	10-14%	0.3-0.8%	280
DF Surrogate	27%	47%	26%	N/A	< 0.5%	280

For the Douglas-fir surrogate, the downward smoldering velocities and peak temperatures were estimated by interpolating from previous results with lignin, cellulose, and hemicellulose. The tests encompassed the range of contents and densities and had low inorganic content (downward tests were also performed at 200 kg/m²). This was not possible for wheat straw (inorganic content was too high) or for the horizontal propagation velocity in Douglas-fir (no tests were available at densities $\geq 280\text{kg/m}^3$). Wood ash was used for the inorganic content. For the surrogate study, hemicellulose was also used to account for the "Other" organic material. This was chosen because the "Other" organic material generally breaks down relatively easily compared to other organic constituents [69], and hemicellulose breaks down more readily than cellulose and lignin [65, 66]. An alternative for the "other" organic material could be developed in the future.

The smoldering behavior of eastern red cedar, apple wood, and grass seed screenings have also been tested. However, their corresponding surrogates have not been tested at this report's time of drafting.

4.2 Evaluation of Influence of Particle Size on Smoldering Behavior

The size of the particles that burn can influence smoldering behavior by changing the level oxygen available for reactions and the dominant modes of heat transfer. Section 4.2 summarizes efforts to specifically identify the effect of particle size on smoldering behavior.

4.2.1 Sample Preparation

Smoldering experiments were conducted with premium grade 100% Douglas-fir wood pellets. The chemical composition of the wood pellets was determined through the wet reference method at an external forage testing laboratory. The wood pellets had a lignin content of 23.1 – 31.3%, a cellulose content of 40.2 – 46.5%, a hemi-cellulose content of 10.1 – 14.1%, and an ash content of 0.3 – 0.8%. The wood pellets were put through a Stokes model 43 granulator to reduce the particle size. The granulator screens used were made of stainless-steel wire cloths with square opening characteristic sizes of 0.91 mm and 2.36 mm. The granulated particles were then sifted through sieve screens to further define the particle sizes. The ranges of the diameter of the particles investigated were $3.18\text{ mm} > d > 2.12\text{ mm}$, $2.12\text{ mm} > d > 1.27\text{ mm}$, $1.27\text{ mm} > d > 0.85\text{ mm}$, $0.85\text{ mm} > d > 0.51\text{ mm}$, and $d < 0.51\text{ mm}$. The samples were stored in enclosed

containers to minimize changes in moisture content, resulting in measured moisture contents of 5 – 11% at the time of testing.

4.2.2 Horizontal Smoldering Experiments

The experimental arrangement for inducing ignition and measuring propagation rates is shown in Figure 4.2.1. Included in the arrangement is an infrared (IR) camera, stainless-steel mirror, reactor box, co-flow, and cartridge heater. The reactor boxes, made of stainless-steel plates, had dimensions of 203.2 mm x 203.2 mm x 76.2 mm; and were separated by $\frac{3}{4}$ in thick wood placeholders.

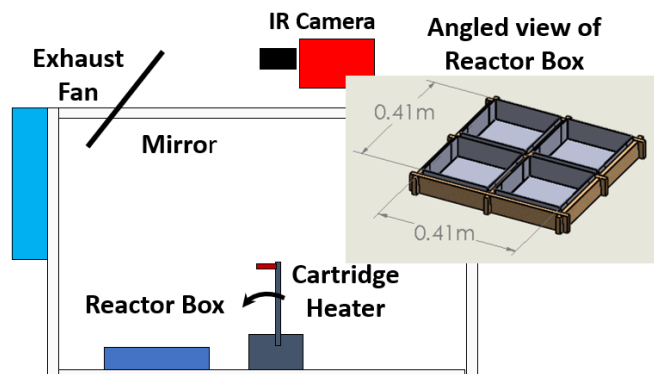


Figure 4.2.1 Arrangement used to conduct smoldering experiments.

A co-flow of air was placed around the reactor box to minimize changes of the surface conditions as ambient conditions in the laboratory varied. The co-flow controlled the relative humidity on the surface of the sample at an estimated value near 50% with a standard deviation of 11% [71]. The co-flow was heated as well, resulting in an estimated mean temperature near 14°C at the samples surface.

Three ignition methods were used during testing. The different methods were used to help identify if changes in the initial heat transfer characteristics altered ignition behavior. For all three methods a cartridge heater was placed in the center of each box of the fuel bed. With the first ignition approach, samples were ignited using a 30 W cartridge heater. The heater was placed in contact with the fuel upon reaching a temperature $> 370^{\circ}\text{C}$. Within 5 minutes, the heater temperature increased to $500^{\circ}\text{C} \pm 25^{\circ}\text{C}$ and was held at that temperature using a PID thermocouple controller. The heater remained in the sample for 20 minutes after which it was removed. In the second approach, samples were ignited using the same 20 W heater. However, the heater was placed in contact with the fuel at room temperature and increased to $345^{\circ}\text{C} \pm 25^{\circ}\text{C}$ using a PID thermocouple controller thereafter. This increase in temperature took approximately 5 min. The heater remained in contact with the sample for 20 minutes upon which it was removed. In the third method, samples were ignited using a 120 W cartridge heater that was placed on the fuel upon reaching a temperature $> 750^{\circ}\text{C}$. The cartridge temperature was increased and then maintained at $800^{\circ}\text{C} \pm 25^{\circ}\text{C}$. The heaters were removed from the sample if flaming was observed. Any flames were extinguished using a leather glove. In all cases, the sample was monitored for 30 minutes to ensure that the sample propagated to sustained smoldering. If the fuel bed was unable to sustain smoldering the experiment was concluded. If the fuel bed was able to transition to sustained smoldering, the burn was allowed to progress. The

smoldering tests were concluded once the smoldering front reached 1.3 cm from the boundaries of the reactor box to minimize the cooling effects of the frame.

A FLIR SC6700 infrared camera was used in all horizontal tests to determine the spread rate and surface temperature of the smoldering reaction. A stainless-steel mirror was used to reduce the interference of smoke released from the reaction and protect the IR camera from the accumulation of soot. The integration time of the camera was set to 4.96 ms and images were acquired every 10 s. The integration time was selected as it corresponded to a temperature range of $80^{\circ}\text{C} < T < 730^{\circ}\text{C}$, which was within the bounds of the surface temperatures observed during the smoldering process. The smoldering surface temperatures ranged from $200^{\circ}\text{C} < T < 500^{\circ}\text{C}$. The window of the camera was set to 640x512 pixels.

4.2.3 Sample Characterization

Prior to ignition, two subsamples were extracted from the corners of the reactor box using a metal tube. The tubes measured 1.27 cm in diameter and 2.54 cm in height. The tube was placed through a section of fuel and the section of fuel was extracted with the help of a preplaced guide. From each reactor box, one subsample was used to measure the porosity and moisture content, and the other subsample was used to find the permeability and bulk density. The porosity was determined using Archimedes' method [72]. Moisture content was determined using ASTM D2974-87 method B [73]. The permeability was determined using Darcy's law with the experimental arrangement showed in Figure 4.2.2.

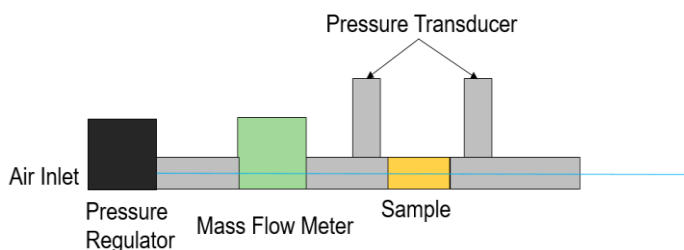


Figure 4.2.2: Experimental setup used to determine permeability of subsamples.

4.2.4 Data Analysis

A black body calibration was used to convert the photon counts obtained from the IR camera to temperatures used in the data analysis. Black body temperatures ranging from 40°C to 600°C were used with an integration time of 4.96 ms as described in Cowan et. al [71]. The emissivity of the samples was assumed to be 0.85, which is similar to values measured in heated wood [74] and ponderosa pine duff [71].

A spatial calibration image was taken prior to each test using a heated plate. The spatial resolution varied slightly between experiments, but typically was 1.04 mm/pixel.

The spread rate was calculated through the change in radius of the burned area throughout the infrared images. This approach assumed that the burned area was circular, and was consistent with the approach used previously [75]. In the rare occurrence where the burn did not smolder in a circular pattern the test was not considered when determining the spread rate. A temperature threshold of 250°C was used to determine which pixels were considered smoldering or non-smoldering during the analysis. This threshold was selected as it corresponds to the temperature at which fuel pyrolysis begins to occur [76].

Once a pixel was considered smoldering it was identified and considered as smoldering throughout the rest of the images. This was done to remove the possibility that a pixel would cool to below the smoldering threshold and no longer be considered smoldering when determining the burned area.

4.2.4 Heat Transfer Analysis

A simplified model of heat transfer through particles of fuel was developed and used to help provide qualitative insights into the role of heat transfer in causing the observed burning and ignition characteristics. It was hypothesized that the smaller particles have less thermal resistance to heat transfer between burning and non-burning particles. The model considered conduction, convection and radiation around a single particle, as illustrated in Figure 4.2.3 and described shortly. Conduction and radiation heat transfer were assumed to transfer heat to adjacent particles while convection transferred heat to the surrounding gases and hindered heat transfer to adjacent particles.

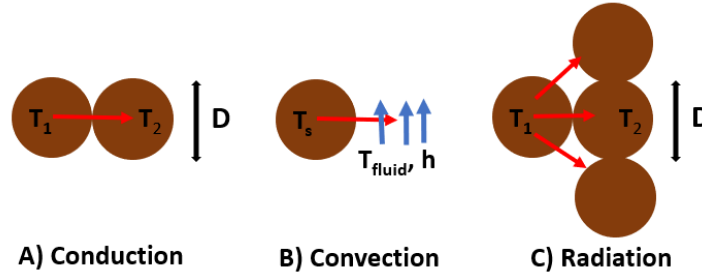


Figure 4.2.3: Control volumes used in conduction, convection and radiation heat transfer analysis.

4.2.5.1 Conduction

The heat transfer by conduction (illustrated in Figure 4.2.3 panel a) was estimated using Fourier's Law. The temperature of the heated particle (i.e., T_s) was assumed to be 300°C and the temperature of the adjacent particle (i.e., T_2) was 20°C. Certainly, in the experiment the temperature of adjacent particles will be hotter, but the assumption of room temperature was sufficient for understanding trends in heat transfer.

The model developed by Campbell et al. [77] was used to determine the effective thermal conductivity of the packed bed samples,

$$\lambda_{eff} = \frac{k_w x_w \lambda_w + k_a x_a \lambda_a + k_m x_m \lambda_m}{k_w x_w + k_a x_a + k_m x_m} . \quad (1)$$

Here k , v and λ denote the weighting fractions, volume fractions and thermal conductivity, respectively. Subscripts w , a , and m represent the water, air and fuel respectively. Physically the effective thermal conductivity represents a weighted sum of the individual thermal conductivities present in the sample material, which include the fuel, air and water. The air and water were assumed to be present in the pores of the sample. In all calculations the moisture content was assumed to be 5% based on laboratory testing. Porosity was calculated from the particle size using the correlations in Sato et al. [78]. Porosity and moisture content were used to determine the volume fractions of water and air within the pores and ultimately determine the effective thermal conductivity.

4.2.5.2 Convection

The convective heat transfer of a single particle,

$$q = \bar{h}A(T_s - T_{fluid}), \quad (2)$$

was investigated to determine the cooling rate from the particle to the surrounding air in the pores (see Figure 4.2.3 panel b). It was assumed that the particles were at a temperature of $T_s = 300^\circ\text{C}$ and the surrounding air was at a temperature of $T_{fluid} = 20^\circ\text{C}$. To determine the particle Reynolds number (Re) a constant flow rate of 250 sccm was assumed throughout the packed bed. This flow rate is much smaller than those used in experiments with forced flow (e.g., flow rates of 120 to 200 l/min [40]). The full surface area of the particles was used to determine heat transfer due to convection. While the experiments did not have forced convection through the fuel beds, it was expected that some air transport occurs near the surface (i.e., where burning occurs) because of natural convection. Reynolds numbers of the flow ranged from 0.01 to 0.1. The correlation,

$$Nu_{kta} = 1.27 \left(\frac{Pr_f^{0.5}}{\varepsilon^{1.28}} * Re_p^{0.36} \right) + 0.033 * \left(\frac{Pr_f^{0.5}}{\varepsilon^{1.07}} \right) Pr_f^{0.86}, \quad (3)$$

was used to determine,

$$\bar{h} = \frac{Nu_{kta} k_f}{D_{particle}}. \quad (4)$$

It is important to note that equations 2 - 4 were originally derived for the packed beds under natural convection in gas cooled nuclear reactors [45], consistent with the flow and geometry expected in the smoldering fuel beds.

4.2.5.3 Radiation

Radiation heat transfer between adjacent particles was determined through a resistance model described in text [79],

$$q = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1 - \varepsilon}{\varepsilon A} + \frac{1}{AF_{12}} + \frac{1 - \varepsilon}{\varepsilon A}}. \quad (5)$$

The emissivity of the fuel was assumed to be 0.85 [74] and a grey body analysis was performed. A packed bed model was created to determine the view factor for the analysis. The heated particle was assumed to be at a temperature of 300°C and the particle being heated was assumed to be at a temperature of 20°C , consistent with temperatures assumed for conduction and convective heat transfer. The heat rate of radiation was determined through use of a resistance network from the heated particle to the adjacent particle as seen in Equation 5.

4.3 Identifying the Influence of Wind on Smoldering Behavior

Wind can alter smoldering behavior by changing both the heat transfer and oxygen availability, as noted earlier. Section 4.3 reviews experiments conducted to identify how changes in wind speed alter smoldering behavior.

4.3.1 Experimental Approach

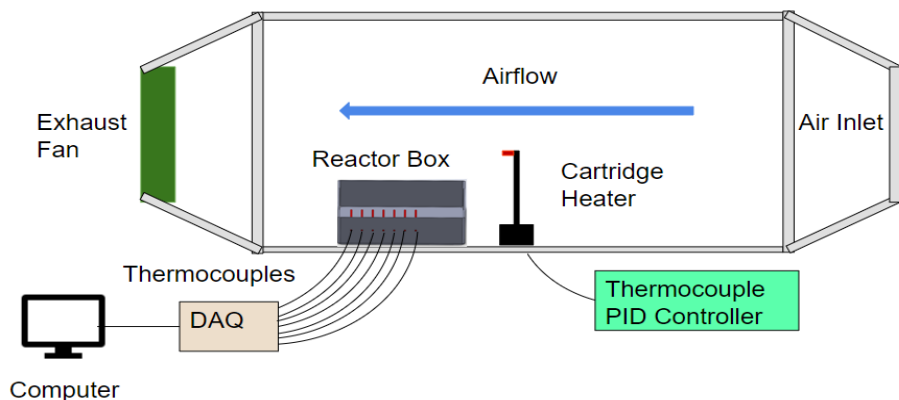


Figure 4.3.1: Experimental arrangement used to conduct smoldering experiments.

The experimental arrangement is shown in Figure 4.3.1. A wind tunnel was used to produce known wind speeds over the burning sample in the reactor box. The wind tunnel consisted of an inlet plenum, a test section of constant area, and an exhaust fan placed in the diffuser, that drew air over the smoldering sample and through the wind tunnel. The wind tunnel was controlled by adjusting the frequency [Hz] of the fan, via an ABB H400-04 series controller. The test section of the wind tunnel measured 0.3 m x 0.6 m x 0.46 m. Five wind speeds were investigated varying from 1 m/s to 5 m/s incremented by 1 m/s.

A reactor box containing the fuel measuring 0.17 x 0.17 x 0.05 m was placed in the test section of the wind tunnel. An array of 7 type-K thermocouples were placed halfway through the side of the reactor box perpendicular to the flow, each separated by 0.015 m. The thermocouples were placed 0.013 m below the surface of the fuel. The thermocouples were connected to a National Instruments model NI SCXI-1000 DAQ with built-in signal conditioning allowing for low-noise measurements. A National Instruments model NI SCXI-1303 isothermal terminal block was used in addition to the DAQ. The isothermal terminal block was equipped with an isothermal copper plane that reduced the temperature gradient across the screw terminals and a cold-junction providing thermocouple measurement accuracy of ± 0.5 °C. A Labview program was used to record and save the temperatures of each thermocouple at a frequency of 1 Hz.

Ignition was achieved using a 30 W cartridge heater. The cartridge heater was placed in the fuel behind the first thermocouple at a depth of 0.0254 m. Once in contact with the fuel the cartridge heater was powered and heated to a temperature of 550 °C. The cartridge heater temperature was regulated at 550 ± 25 °C utilizing a PID thermocouple controller. At this time the DAQ reading the thermocouple values was energized and began recording. The cartridge heater was removed from the sample once the smoldering front propagated 0.0254 m from the center of the cartridge heater, this occurred at approximately 8 min from contact with the fuel. At this time the cartridge heater was removed from the wind tunnel test section and the wind tunnel was sealed and turned on.

With the cartridge heater removed and the wind tunnel turned on, the smoldering front was allowed to progress across the reactor box. The experiment was concluded once the last thermocouple in the reactor box reached 350 °C. At this time the DAQ was turned off and data recording was stopped. The smoldering reaction within the wind tunnel was extinguished and the experiment was concluded.

4.3.2 Wind Tunnel Calibration

A pitot tube in conjunction with a pressure transducer was used to determine the wind speed. A NIST PCL-1B pressure transducer utilizing a GQS-38529 module capable of measuring pressure in the range of 0-2.488 kPa (0-10 inH₂O) was used and operated independently of the DAQ with a handheld unit. The pressure transducer measured the differential pressure between the total pressure and static pressure pitot tube ports allowing wind speed to be determined using the relationship,

$$v = \sqrt{\frac{2\Delta P}{\rho}} \quad (1)$$

For the calibration wind speeds, various fan frequencies were tabulated and plotted. A best fit linear line was applied to the tabulated data and used as the calibration curve for the wind tunnel. Due to high uncertainties at low wind speeds (14 to 20%), the wind tunnel calibration was performed at higher wind speeds than used in the experiments. Lower wind speeds used in the experiment were then extrapolated from the calibration. This method significantly reduced the uncertainty in the wind speed measurements (4.9%).

4.3.3 Uncertainty Analysis

A design stage uncertainty analysis was performed for each measured value in the experiment. Temperature values throughout the experiment were between 20°C and 750°C. Because the smoldering fronts in this experiment moved slowly, high temperature resolution and high speed responses were not needed. The type-K shielded thermocouples used had a temperature range of 0 to 1250 °C with an uncertainty of ± 2.2 °C.

In previous smoldering experiments, utilizing the same fuel and ignition method under windless conditions, spread rates of 0.65 mm/min were observed [75]. In this experiment the smoldering fuel subjected to a crosswind increased the speed of the smoldering front when compared to windless conditions. The design stage uncertainty of the spread rate was determined to be 0.2%. Higher order uncertainties including the instrument uncertainty, described above, and precision uncertainty with 95% confidence are reported later.

Packing density was maintained at 200 kg/m³ for the studies with the wind speed varied. Low variability in the packing density between experiments is important as changes in packing density can cause changes in the observed smoldering temperatures and spread rates [75]. The design stage uncertainty for the packing density was determined to be 1.4% or ± 10 kg/m³.

Wind speed is another crucial measurement for this experiment. After performing the calibration of the wind tunnel described above, the design stage uncertainty of the wind speed was determined to be 4.9% or ± 0.12 m/s.

4.3.4 Fuel and Sample Characterization

The fuel used in the wind studies was 100% cellulose. Cellulose is commonly used as a surrogate fuel in fire research due to the primary organic matter in plant litter consisting of combinations of cellulose, hemi-cellulose, and lignin [80]. The combination of these components in natural fuels is dependent on fuel type and stage of decomposition. Therefore, combinations of cellulose, hemi-cellulose, and lignin can be used to mirror natural fuels found in nature by reproducing the percentage of the constituents in real forest fuels. In this study, 100% cellulose was used as a baseline for further research into the effects of wind on the smoldering temperatures and spread rates of surrogate fuels.

4.3.5 Data Analysis

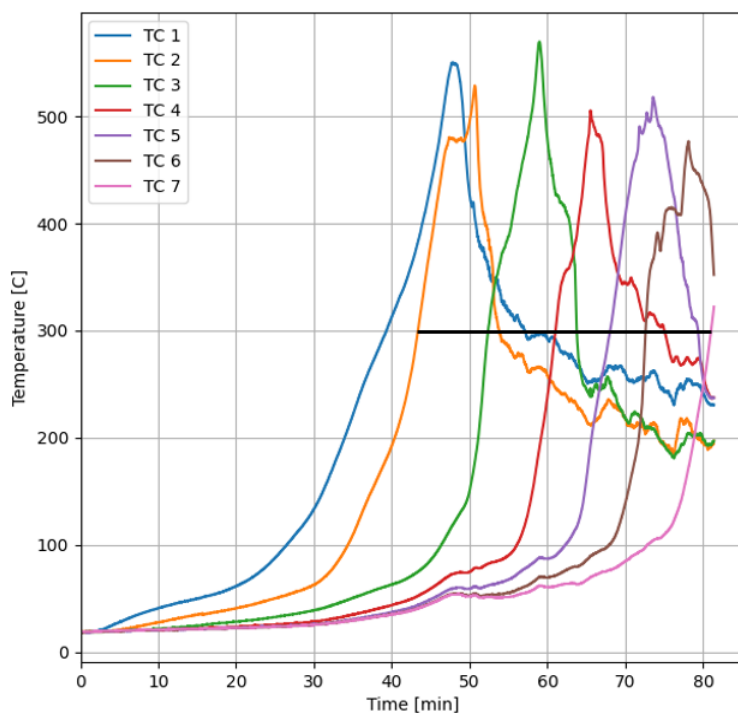


Figure 4.3.2: Time resolved temperature data for each thermocouple used in the experiment. The data is from a test at a wind speed of 3 m/s.

Thermocouple temperatures were collected and plotted to determine time-resolved temperature information. The peak temperatures for each thermocouple were determined from the tabulated data and the overall peak temperature was reported. The spread rates were determined by finding the time difference required for the 2nd and 7th thermocouples to reach a temperature of 300°C, as seen in the horizontal black line in Figure 4.3.2. Admittedly, the temperature threshold is arbitrary, but more importantly, it was a consistent value that was used. With the known distance between the thermocouples, the spread rates were determined. The 2nd thermocouple was used in place of the 1st to ensure that heating from the cartridge heater did not affect the results.

4.3.6 Limitations

Since the thermocouples were placed 13 mm below the surface of the fuel, only subsurface smoldering propagation rates and temperatures were measured. To measure surface conditions, an infrared (IR) camera should be used in future work. Additionally, changes in the velocity

field due to the reactor box were not considered. The wind speeds reported are bulk flow velocities and are not necessarily representative of the velocity just above the reactor box.

4.4 Smoldering Behavior of Field Samples

The field studies consisted of a combination of burning samples in the field and collecting samples from the field and burning them in the laboratory. These experiments are being used to help address Objectives 5 and 7. The latter allows some control over moisture content (through drying) as well as greater control over external factors such as wind speed, temperature, humidity, and solar flux.

Seven burns in the field underneath ponderosa pine trees and over 50 field samples (of ponderosa pine and Douglas-fir duff) burned in the laboratory have been conducted. The initial four field burns were plots set up in a controlled burn in Winthrop, Washington (WA), but the initial combustion that passed over was flaming, which biased the results. The next three burns were individual smoldering plots set up in Winthrop, WA. Three field samples for burning in the laboratory were collected near Sisters, Oregon, (OR) and two from Silverlake, OR.

4.4.1 Experimental Arrangement

Figure 4.4.1 shows the experimental arrangement for visualizing the smoldering behavior of duff burned in the field. A similar arrangement was used to burn duff samples that were extracted and burned in the laboratory. Additional information about the approach for burning samples in the laboratory is provided in Section 4.2. An infrared camera was used to visualize the propagation of the smoldering front via a mirror placed above the sample. Thermocouples were inserted into the duff for some burns to measure temperatures.

Field samples were selected from underneath mature ponderosa pine and Douglas-fir trees. The former fuel had a minimum of 10 cm of duff after the upper litter layer (e.g. fresh needles, twigs) was removed. The typical thickness of the subsamples was extracted from the corners of each plot prior to burning, which were used to determine the depth of both the fermentation layer (upper duff layer) and humus layer (lower duff layer), bulk density, moisture content, and inorganic content. Moisture content was calculated on a dry-weight basis for each subsample by recording subsample mass immediately after removal and then after drying in an oven set at 120°C for five days. Similarly, inorganic content was measured as the fraction of mass left after a subsample was heated at 600°C until complete combustion of the organic material occurred.

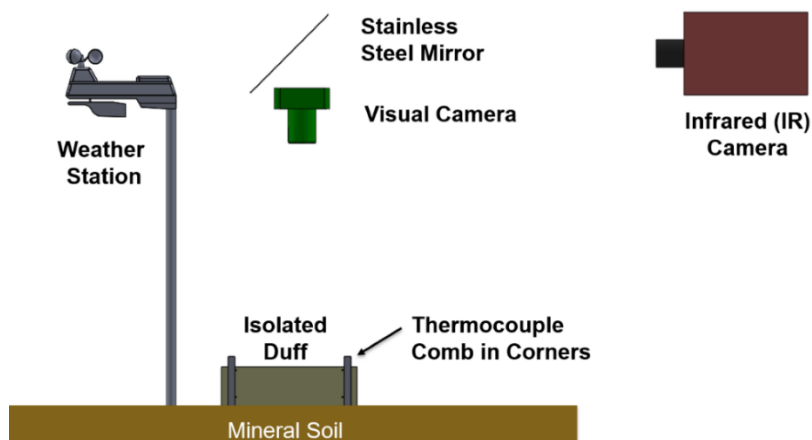


Figure 4.4.1: Experimental arrangement for visualizing burns in the field.

Plots burned in the field were 50 x 50 cm with the thermocouple arrays inserted towards the center of the plots from each of the four corners. Field samples burned in the laboratory were dimensioned 47 x 47 cm and extracted to the depth of the mineral soil layer. The samples were stored within a cardboard box and two thermocouple arrays were inserted 15 cm from one side of the sample towards the center.

Both the field samples and field studies were ignited using a 1,500 W heat gun. Specifically, a three centimeter diameter area within the center of the plot was heated until flames appeared. The flames were then extinguished by smothering with a leather glove. The area was monitored, and if ignition did not occur the process was repeated.

4.4.2 Data Processing

The IR images were used to determine surface temperatures and propagation velocities based on a sampling rate of 0.1 Hz and a temperature threshold of 200°C. Specifically, the boundary of the smoldering front from the images was found every ten minutes and the shortest distance between the smoldering front's position and the previous time step boundary was determined. This value was converted into propagation velocity vectors by using the spatial calibration and a ten-minute time step (Figure 4.4.2 left panel). The vectors were then used to find the range of propagation velocities for each burn experiment (Figure 4.4.2 right panel). The distribution has a range of velocities. The propagation velocity can be as large as eight (mm/min), which is a difference of a magnitude compared to the propagation velocities found in the laboratory studies. It is hypothesized that the variety of velocities are caused by wind, and differences throughout the duff.

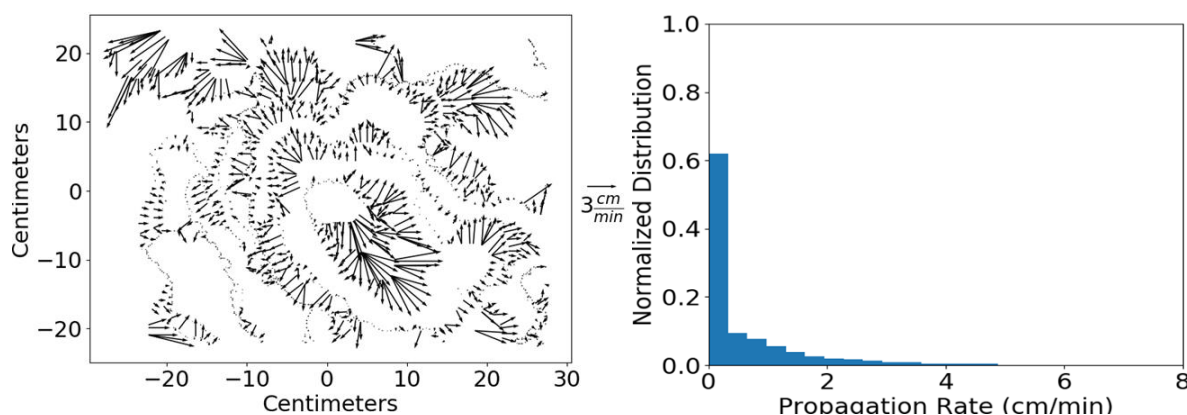


Figure 4.4.2: (Left panel) The smoldering propagation velocity vectors for a ponderosa pine field burn near Winthrop, WA. (Right panel) The normalized distribution of the propagation velocities.

4.5 Measuring Emissions from Smoldering Samples

4.5.1 Emission Collection and Analysis

Emissions measurements were taken of smoldering duff in laboratory and field studies. The field studies isolated a duff sample within the forest which allowed for smoldering to be monitored in its natural environment.

The approach to emissions sampling was to measure the rate of carbon emissions per unit area. This was accomplished by placing a small cubic chamber (0.027 m³) onto the smoldering section of the plot. The sampler consisted of a 12-volt KNF canister pump plumbed with stainless steel

tubing, a pressure relief valve and pressure gauge. The sampler was connected to the sampling chamber with a flexible line. Each smoldering measurement consisted of two canister samples - prior to the emissions sample a background canister sample from the chamber was collected with the chamber, to establish the initial concentration of gases in the chamber. Then the chamber was placed onto the actively smoldering isolated duff section of the plot. The chamber filled with emissions from the smoldering duff for a period of 30 to 60 seconds, and then a canister sample was pumped from the chamber into a 0.6L canister. A series of samples was collected after smoldering commenced, at 10 to 20 min. time intervals depending on visible smoke activity.

The canisters were analyzed at the Missoula GC Lab. The concentrations of methane, carbon dioxide (CO₂), carbon monoxide (CO), and non-methane hydrocarbons (NMHC) were determined by gas chromatography following EPA method TO-14A (U.S. EPA 1999) with an Agilent model 7890 gas chromatograph equipped with dual flame ionization detectors. Each FID has a specific column, 10-port valve in a heated zone, gas sampling loop, and plumbing setup.

The C₁–C₆ analyses were performed using a 0.25 ml sample loop, a 5 m HP-1 pre-column, a 0.53 mm x 30 m Al/S (Agilent) column, helium carrier gas at 6 ml/min., and FID at 300°C, with a makeup helium gas flow of 14 ml/min. The sample was injected on to the pre-column, then at 1 minute a 10-port valve vented the sample flow coming from the pre-column to exhaust, to prevent heavier hydrocarbons going through the main column and on to the detector.

The CO₂ and CO analysis used a 10-port valve with a 1 ml sample loop to inject the sample, a 1/8" diameter x 6 ft. Carbosphere (Alltech) column to separate CO₂, CO, and air, helium carrier gas at a flow rate of 16 ml/minute. After separation in the column the sample entered a nickel catalyst methanizer (375°C), that converted the CO₂ and CO to methane, then on to a flame ionization detector (FID), temperature 350°C. The column was backflushed for 15 minutes, after elution of the CO₂ peak. The oven temperature programmed for these simultaneous analyses was 50° C for 6 minutes, then increased by 10°C/ minute to a final temperature of 150° C for 8 minutes.

The net ppm concentration of each gas was determined by subtracting the corresponding background canister sample results from the smolder sample concentration. For each sample the carbon content of each gas was summed to calculate the total carbon concentration generated in the chamber. Based on the sampling time, the rate of carbon emission was calculated, per area based on the footprint of the chamber.

Fire-integrated emission factors were calculated using the carbon mass balance (CMB) approach (Ward and Radke 1993), in which the concentrations of emitted carbon-containing species are a proxy for the mass of dry fuel consumed during the fire. The emission factor for species *i* emitted by a fuel with carbon mass fraction (*x_c*) of the dry fuel mass is given by:

$$EF_i = \frac{m_i}{\Delta CO + \Delta CO_2 + \Delta PM_C + \sum(\Delta HC)} x_c \quad (1)$$

where *m_i* is the mass of species *i* emitted, *PM_C* is the mass of particulate-phase carbon and $\sum HC$ is the sum of the total mass of C contained in gas-phase hydrocarbons, estimated as the sum of the measured C_{1–6} hydrocarbons. Combustion efficiency (CE), the fraction of volatilized carbon emitted as CO₂ was calculated for all samples.

Modified Combustion Efficiency (MCE) was also calculated for each sample. MCE is a normalized ratio of CO and CO₂ and gives a good indication of the type of combustion. It is

normalized by dividing the CO₂ carbon by the sum of carbon contained with the CO and CO₂; it becomes linearly correlated with other products of incomplete combustion:

$$\text{MCE} = \text{CO}_2 \text{ ppm} / (\text{CO ppm} + \text{CO}_2 \text{ ppm})$$

An MCE value of 0.95 to 1.00 indicates mostly flaming combustion. MCE less than 0.85 indicates smoldering combustion, a lower MCE predicts a higher level of smoldering and more CO and VOCs emissions vs. CO₂. Teflon filter sampling was also performed in the laboratory experiments to measure PM_{2.5} particulate concentrations in the smoke. The sampling system consisted of a custom system designed and assembled in house, consisting of a pump (Thomas model SR-0300), flow controllers, control electronics, and a URG model 2000-30EH 2.5µm cut point Teflon coated aluminum cyclone, with a flow rate of 16.7Lpm. The Teflon filters were Teflo (Pall Corp.) 1 µm pore size, 37mm diameter. The sampling pump was calibrated with a Gilibrator-2 air flow calibrator device. Flow rate and time of sampling were logged.

The 37 mm Teflon filters are conditioned and weighed in a controlled-environment room at 20°C and 35 percent relative humidity. Prior to weighing, the filters are conditioned for at least 24 hours. Each filter is weighed three times on a Mettler M4 microbalance with a precision of one microgram (µg). The balance is linked to a software program that collects and stores the weights and room condition. The balance is tared (zeroed) before each weighing. A calibration weight is used once every five filters to verify the accuracy and calibration of the microbalance. Filters whose weights are not reproducible to within 5 µg are withheld from analysis. Control filters are used to correct for environmental and handling variability in the filter weights. The control filters are handled in the same way at the treatment filters. Each filter is pre-weighed prior to sample collection using this procedure, and then again after field collection. They are again conditioned at least 24 hours to stabilize the particulate matter weights and to reduce the effects of static electricity on the weighing process. The PM_{2.5} concentrations are calculated using a Visual Basic software program, based on the final particulate matter weights (post-weight minus pre-weight), control filter results, and the volume of air drawn through the filter during the emission sampling.

4.5.2 Field Collection

In 2017, emission samples in the field were taken from two prescribed fires that burned through a plot and three single tree point source experiments. The experiment sites were on the Methow Ranger District, Okanogan National Forest, Washington. The forest vegetation is a mix of ponderosa pine and Douglas Fir with a shrub and grass understory. The samples were taken within the square formed by the four thermocouples on the field established plots. Depending on the site samples were taken at 15 to 20 minutes intervals initially during active smoldering, usually with an hour of the flame front passing. For the point source burns, after ignition in the center of the plot and smoldering was established, sampling began, and was performed hourly.

4.5.3 Emission Sampling During Laboratory Experiments

Emissions were measured in two of the laboratory experiments – January 2020 and May 2021. After ignition and smoldering became active the sampling began in the 47 x 47 cm duff, the emission sampling method was identical to the field method, with the exception that a background sample was not collected before each smoldering sample. The lab background gas concentration was measured twice a day. It did not change significantly as the smoke emitted from the duff was ventilated to the outside. Particulate samples on Teflon filters were also collected. Samples were taken at 10 - 20 min. intervals until smoldering emission was minimal.

4.6 Computational Approach

Numerical models were developed and used to help address Objectives 1, 2, and 4. A one-dimensional reactive porous media model was developed using the open-source software Gpyro [28]. This model was used to simulate smoldering of multiple woody and biomass fuels relevant to wildland fire. Gpyro solves one-dimensional transient equations for condensed and gas-phase mass and species conservation, as well as condensed-phase energy and gas-phase momentum equations, and the ideal gas equation of state. In this model, the condensed and the gas phase are assumed to be in thermal equilibrium, and Gpyro takes the shrinkage of the sample during the smoldering process into consideration. The Schmidt number was taken as unity. All simulations were run with an initial time-step size of 0.05 s and cell size of 10^{-4} m, was selected after some analysis to keep a balance between accuracy and simulation time [29].

All of the computational studies used a one-dimensional domain intended to simulate downward propagation of smoldering. The top surface of the domain was modeled as being open to atmosphere, allowing both convection and mass transfer. The bottom surface was set as insulated, but with some small heat transfer to account for losses (via a heat transfer coefficient of $3 \text{ W/m}^2\text{K}$).

The fuel bed was ignited using two mechanisms, depending on the focus of the particular set of simulations. Most cases used an applied heat flux at the top boundary, held constant for a particular amount of time (e.g., 25 kW/m^2 for 20 minutes) until the sample smoldered. In turn the boundary was replaced with a convective-radiative balance boundary condition. Certain simulations focused on the effects of moisture content kept a constant heat flux throughout the entire simulation to guarantee ignition.

Some simulations examined ignition due to a hot metal particle landing on the surface of the fuel bed. In these cases, the domain included an upper layer (with variable thickness) with the materials of the metal in question (aluminum or steel). The metal was assigned an initial temperature, and then the interface surface between the metal and fuel bed used the same upper boundary conditions as in other simulations to allow heat and mass exchange with the atmosphere.

4.6.1 Physical Parameters

For simulations performed to validate our model, we used the experimental measurements of bulk densities of cellulose and hemicellulose: 175 kg/m^3 and 695.71 kg/m^3 , respectively. All other simulations used the physical properties of condensed-phase species given in Table . The bulk densities of char and ash were calculated using the relations $\rho_{char} \approx \nu_{char} \times \rho_{fuel}$ (Where ν_{char} is the stoichiometric coefficient of char from a particular fuel component) and $\rho_{ash} = AC/100 \times 10 \times \rho_{fuel}$, where AC stands for ash content [36, Personal communication X Huang 25 March 2017]. The AC for cellulose, hemicellulose, and lignin are taken as 0.3%, 1.2%, and 1.4%, respectively [29, 81]. The bulk density of the mixture in the model was calculated by taking into account the bulk density of cellulose and hemicellulose before mixing and mass fraction of those species in the mixture using the relation $\rho_{mixture} = \left(\frac{Y_{cellulose}}{\rho_{cellulose}} + \frac{Y_{hemicellulose}}{\rho_{hemicellulose}} + \frac{Y_{lignin}}{\rho_{lignin}} \right)$. The values of the pore diameter, permeability, and parameters controlling the radiation heat transfer across pores of condensed phase species were calculated using relations provided in Huang et al. [82]. Other thermo-physical properties, which include solid density, thermal conductivity, and heat capacity of cellulose, hemicellulose, lignin, char, and ash, were compiled

from the literature [82–87]. Table 4.6.1 contains the physical properties of aluminum and steel, used for the simulated hot metal particles. Since temperatures in some simulations reach the melting point of aluminum, we needed to consider molten (liquid) aluminum properties; the melting point of steel (~1693 K) was not reached in any simulations.

Table 4.6.1. Physical properties of condensed-phase species

Species	Solid density (kg/m ³)	Thermal conductivity (W/(mK))	Heat capacity (J/(kg K))
Cellulose	1500	0.356	1674
Hemicellulose	1365	0.34	1200
Lignin	1305	0.39	1147
Char	1300	0.26	1260
Ash	2500	1.2	880
Water	1000	0.6	4186
Aluminum 1100	2710	220	900
Aluminum 1100 (molten)	2375	90.7	1141
Steel 302/304	7860	21.5	1693

We also simulated smoldering in specific fuels, particularly some relevant to wildland fire, composed of different proportions of cellulose, hemicellulose, and lignin. Table shows the composition of fuels, on a mass fraction basis [88–92]. For fuels where the literature contained multiple composition values, we chose the mostly widely used. For example, for duff we considered the composition of one-year decomposed duff from Scots pines [88]. For all fuels, these simulations assumed that extractives are not present. Duff and peat are the major fuels that undergo smoldering combustion in forest fires, and lignin is the major constituent in both. Duff is present mostly in the middle fermentation horizon in forest beds, characterized by partially decomposed litter. Well-decomposed duff will be in the bottom humus layer. Peat is mostly considered to be in the bottom humus of well-decomposed organic matter [93]. Lignin decomposes slower than cellulose and hemicellulose [88], so the lignin component is higher in duff and peat. Twigs are in the top litter of forest beds, and they are less decomposed, so the hemicellulose content is higher in these fuels. Smoldering can be initiated in this top litter layer in forest beds, so understanding its behavior is also important. Pine needles can be present in top litter to middle fermentation layer depending on the decomposed level; we considered a more-decomposed pine needle [92]. We also considered a mixture of grass blends in order to compare our results of smoldering spot ignition with the study by Urban et al. [12]. In contrast, cellulose makes up around 50% of softwood and hardwood, and paper mostly consists of cellulose, which we considered to represent a high-cellulose fuel.

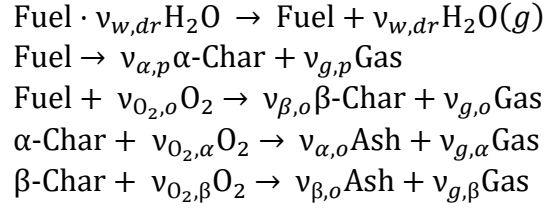
Table 4.6.2. Composition of real fuels considered

Species	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Duff	35	22	43
Peat	28	10	62
Softwood	44	26	30
Hardwood	44	34	22
Twigs	18	52	30
Paper	75	15	10
Pine needle	41	28	31

Grass blend	42	30	28
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4.6.2 Chemical Kinetic Parameters

We adopted a global scheme of reactions to simulate smoldering, with five reactions for each constituent (cellulose, hemicellulose, and lignin): a drying step, a pyrolysis step for each fuel, and three oxidation reactions of fuel, β -char, and α -char [18, 82]. In total the chemical kinetic model included 15 global reactions, with 15 condensed-phase species and 4 gas-phase species. The following five reactions were repeated for cellulose, hemicellulose, and lignin:



where v is the stoichiometric coefficient; and α and β indicate char produced from fuel-pyrolysis and fuel-oxidation reactions, respectively. We obtained the chemical kinetic parameters (pre-exponential factor, activation energy, order of reaction, and heat of reaction) from Huang and Rein, stoichiometric coefficients for cellulose from Kashiwagi and Nambu, and for hemicellulose and lignin from Huang and Rein [18, 82, 94]. The consumption of oxygen (i.e., stoichiometric coefficient) was calculated using $\Delta H/(-13.1)$ MJ/kg.

4.6.3 Moisture Content

Most simulations used a moisture content of 10%, to account for the moisture present in natural fuels. In addition, in some cases we specifically varied the moisture content. Moisture content was considered via a drying step in the reaction scheme. The reaction parameters for the drying step were obtained from Huang and coworkers [25]. The addition of water also changes the density of the (wet) fuel, and we accounted for this change using

$$\rho_{\text{wet fuel}} = \rho_{\text{dry fuel}} \times (1 + \text{MC})$$

where MC is the moisture content [25]. When we added water to the sample there was an expansion in the fuel. To investigate the role of this natural fuel expansion, we considered cases where the fuel expands with moisture content and where it does not; when the fuel does expand, we use the correlation developed for peat by Huang and Rein [23] with the bulk density modified for the fuels considered here. Porosity changes less than 5% with this change in density here, so we consider this adoption justified. The modified correlation is

$$\rho_{\text{dry fuel}} = \frac{200 + 40\text{MC}}{1 + \text{MC}}.$$

4.6.4 Calculation of Global Quantities

The two main parameters of interest are mean propagation speed of smoldering and mean peak temperature. We calculated propagation speeds by numerically computing the derivative of depth with respect to time of peak temperature; in other words, the difference between two depths divided by the times when those depths reach their maximum temperature. This approach requires selecting a depth interval for evaluating this finite difference. To determine the appropriate interval value for calculating mean propagation speed we systematically reduced the

depth interval and examined the effect on calculated mean propagation speed. (A smaller depth interval requires both producing and evaluating more data from the simulations, so we sought a pragmatic choice that affects the results little while reducing the computational burden.) After reducing the depth interval to 1 cm, further reduction negligibly affects propagation speed: reducing from 1 cm to 0.5 cm increases the calculated speed by less than 0.3%. As a result, we chose a 1 cm depth interval for all cases. The supplementary material shows the effects of reducing depth interval on propagation speed in more detail. The mean peak temperature was calculated similarly by averaging the peak temperatures every 1 cm.

5. Results and Discussion

This section discusses how the technical approaches summarized in Section 4 have been used to help address the objectives of this project. A summary of key results and findings are reported. For additional information interested readers are referred to the conference and peer reviewed publications listed in the Appendix.

5.1 Effect of Fuel Chemistry on Smoldering Behavior

A full description of the findings with regards to the influence of cellulose and hemicellulose on smoldering behavior has been published in the Proceedings of the Combustion Institute [62]. What is reported here is a summary of the most significant results and findings.

5.1.1 Horizontal Propagation of Cellulose and Hemicellulose Mixtures

In the initial round of testing with cellulose and hemicellulose, the fuels were loosely packed, and the fuel contents were varied from 100% cellulose to 0% cellulose, with the remainder being hemicellulose. The resulting horizontal propagation velocities are shown in Figure 5.1.1. For these conditions, the propagation velocities increased from 0 to 100% cellulose by roughly a factor of four. However, the density increased by roughly a factor of four during these experiments, as a result, it was not evident if the change in propagation was due to the density or fuel content. To help with further identifying the cause of the sensitivity, the fuel samples were packed so that the fuel content was constant, and fuels were tested with contents ranging from 50% to 100% cellulose, as shown in Figure 5.1.2. This range was chosen because cellulose is more common than hemicellulose in natural fuels [61], and because this was the range where a constant density could be achieved. Once density was accounted for, the propagation velocity decreased with increasing cellulose content; the velocity decreased by about 50% from 50 to 100% cellulose. This indicates that the decrease in propagation velocity in Figure 5.1.1 was due to changes in density. The decrease in propagation velocity with increasing cellulose content seems to be due to the lower temperatures and char yield with cellulose, as will be discussed further in the Downward Propagation section (i.e., Section 5.1.2).

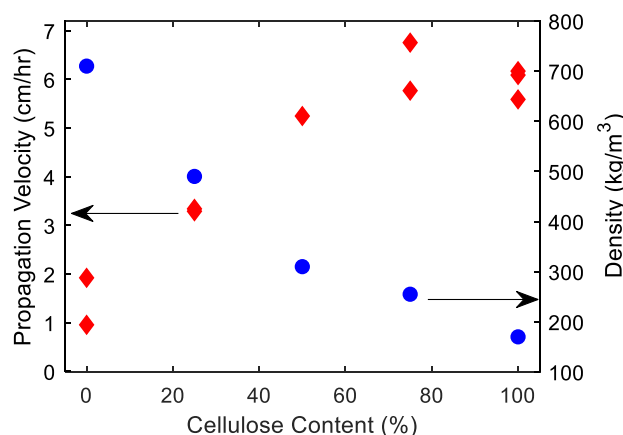


Figure 5.1.1 Horizontal propagation velocities and densities when the fuel content is varied, and the fuel is loosely packed.

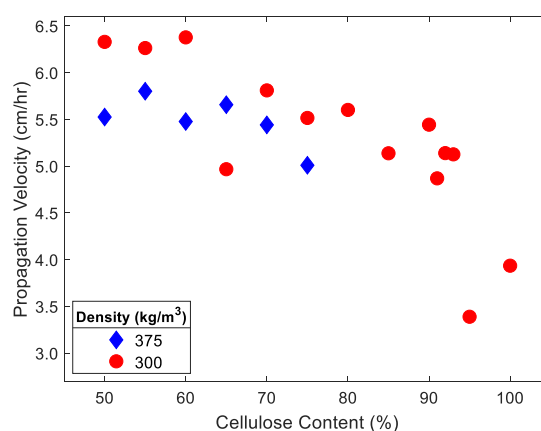


Figure 5.1.2: Horizontal propagation velocities with cellulose content when the density is held constant.

To further investigate the impact of density on horizontal propagation velocities, experiments were conducted where the fuel content was held constant and the density was varied. The results

are shown in Figure 5.1.3. The three fuel contents tested were 100% cellulose, 75% cellulose (remainder hemicellulose) and 50% cellulose (remainder hemicellulose). For all three fuel compositions, the propagation velocities decreased with increasing density. This is largely due to the additional material that needs to be burned. However, cellulose had a notably larger decrease with increasing density than the other two fuel contents. This observation may be due to differences in oxygen diffusion, as the cellulose has longer fibers that can bind together, limiting oxygen availability.

5.1.2 Downward Propagation of Cellulose and Hemicellulose Mixtures

Figure 5.1.4 shows the experimental and calculated downward propagation velocities at varying density for three fuel contents. Like the horizontal propagation velocities, the downward propagation velocities decrease with increasing density for all three fuel contents. However, unlike the horizontal velocities, there is not a notable difference between the fuels with 75% and 50% cellulose. It should be noted that the lack of difference between 75% and 50% was not observed in the initial paper that was published, but a corrigendum including the new data has been published. The decrease with density is on a similar scale, as the fuels decrease by about 30% with a 50% increase in density. The computational values are less than the values observed experimentally, but they do follow the same global trends, as the propagation velocities decrease with density and cellulose content.

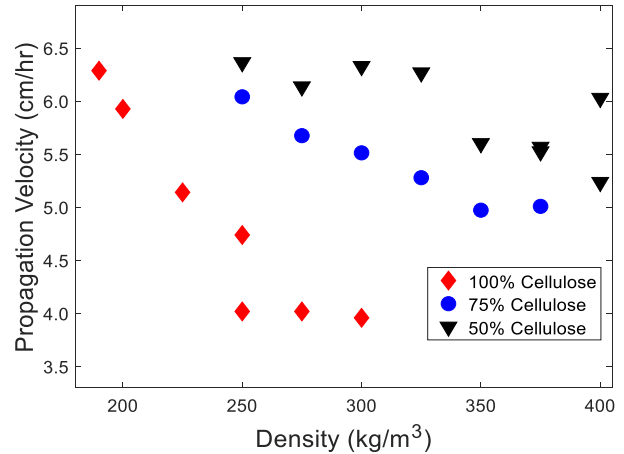


Figure 5.1.3 Horizontal propagation velocities with varying density for three fuel contents. Each data point is for one test.

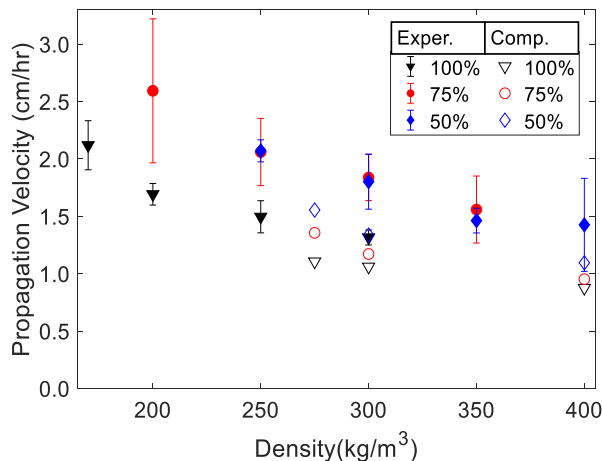


Figure 5.1.4: Experimental and computational downward propagation velocities at varying density and three fuel contents. The experimental values are the mean of 4 to 6 tests.

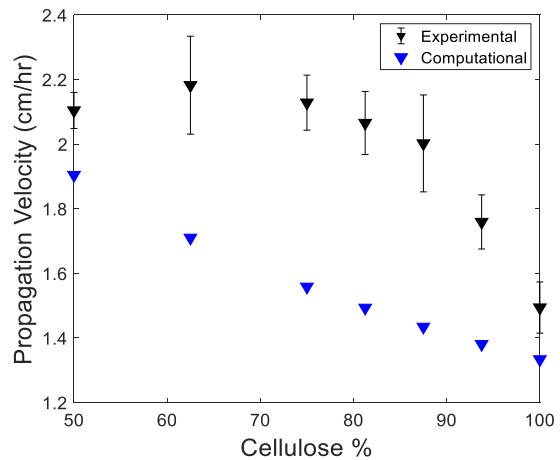


Figure 5.1.5: Experimental and computational downward propagation velocities with varying fuel content. The experimental values are the mean of 4 to 6 tests. The density is 250 kg/m³.

To further investigate the range where the amount of cellulose makes a significant impact on downward propagation, the fuel content was varied at a density of 250 kg/m^3 . The results are shown in Figure 5.1.5. It should be noted that this testing was completed after the publication of the paper and the corrigendum, and as such is not included in either. Experimentally, the downward propagation is roughly steady between 50 and 85% cellulose, but there is a large decrease between 85% and 100% cellulose. This indicates that having some hemicellulose in the fuel can significantly increase downward propagation rates, but that the impact of hemicellulose has diminishing returns beyond a certain threshold.

The computational model was used to gain insights into what is causing the results observed experimentally. In Figure 5.1.6, the calculated temperatures and reaction rates for each component of the fuel are reported. The plot on the left shows differences in the result for two fuels. The fuel with 50% cellulose/50% hemicellulose reaches its peak temperature faster due to the earlier pyrolysis of hemicellulose. Additionally, it reaches a higher temperature due to the higher char yield of hemicellulose. Higher temperatures help the oxidation to occur faster, which also helps increase propagation velocity with increasing hemicellulose content. The plot on the right shows the impact of increasing density. Increasing the density causes a shift in when the reactions occur. This seems to be largely due to the larger amount of fuel, as the peak temperatures and reaction rates are relatively similar.

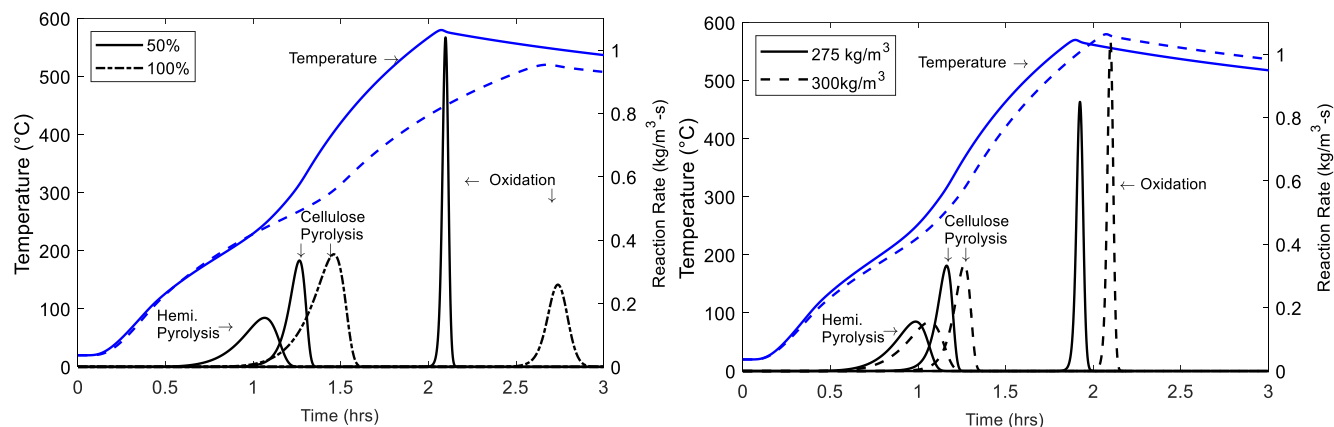


Figure 5.1.6: Computational reaction rates and temperatures for two fuel contents (left) and two densities (right). The density for plot on the left is 300 kg/m^3 , and the fuel content for the plot on the right is 50% cellulose. The oxidation occurs at the same time for both constituents. The location is 3.5 cm below the surface of the fuel.

Comparing the downward and horizontal propagation velocities (see Figure 5.1.7), the global trends are quite similar. Specifically, propagation velocities decrease with increasing density and increasing cellulose content for both cases. However, there are a couple notable differences between horizontal and downward propagation behavior. Specifically, as the sensitivity to the cellulose content is notably larger for horizontal propagation velocities than downward rate. Additionally, fuels with 50% cellulose have faster horizontal propagation than those with 75% cellulose, but this is not observed in the downward propagation. Nonetheless, based on the overall trends, it appears that similar physical and chemical processes controlled both downward and horizontal smoldering under the conditions evaluated.

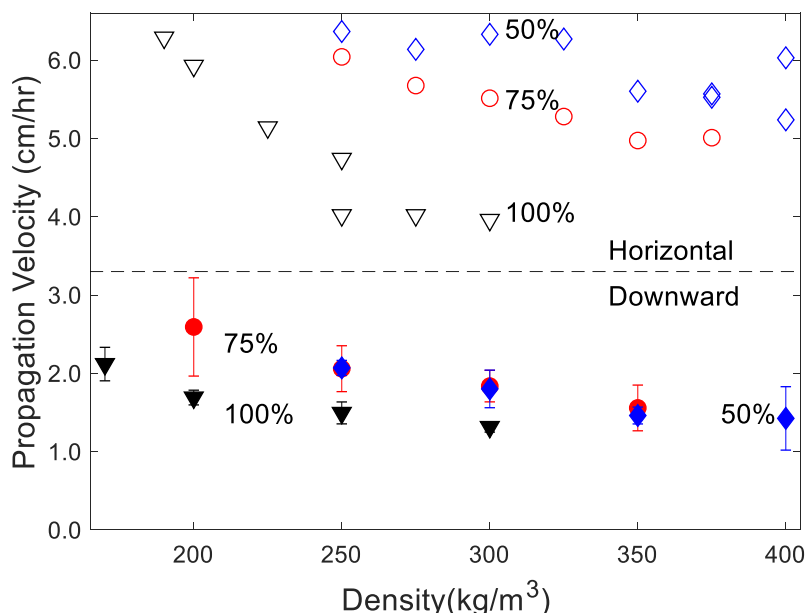


Figure 5.1.7: Experimental horizontal and downward propagation velocities at varying density for three fuels contents.

5.1.3 Effect of Lignin Content on Downward Propagation

Downward propagation velocities, as shown in Figure 5.1.8, were determined at varying lignin contents (and constant density). Corresponding calculations are included for comparison (open symbols) and are discussed shortly. For the non-lignin portion of the fuel, three fuel combinations were evaluated: 100% cellulose, 75% cellulose (25% hemicellulose), and 50% cellulose (50% hemicellulose). Each data point is the average of at least four tests. For all the fuel mixtures, the downward propagation velocities decrease as the lignin content increases from 0 to 30%. These decreases result from the increased activation energy and slower reaction rates for lignin compared with cellulose and hemicellulose. Two additional sensitivities of the propagation rate to the fuel composition are noted. First, the smoldering propagation rate is sensitive to the non-lignin composition of fuel at low lignin contents. This observation is significant because it shows that the smoldering behavior is sensitive to cellulose, hemicellulose, and lignin content in a mixture. For example, the cases with 50% and 100% cellulose in the non-lignin portion of the fuel decrease by about 20% from 0% to 30% lignin, but when the fuel has 75% cellulose, the propagation velocity decreases by 40%. Additionally, fuels with hemicellulose have faster propagation rates than those composed of just cellulose and lignin. Second, the sensitivity of propagation rates to the cellulose/hemicellulose content decreases with

increasing lignin content. This finding suggests that the amount of lignin in the fuel can begin to dominate propagation rates.

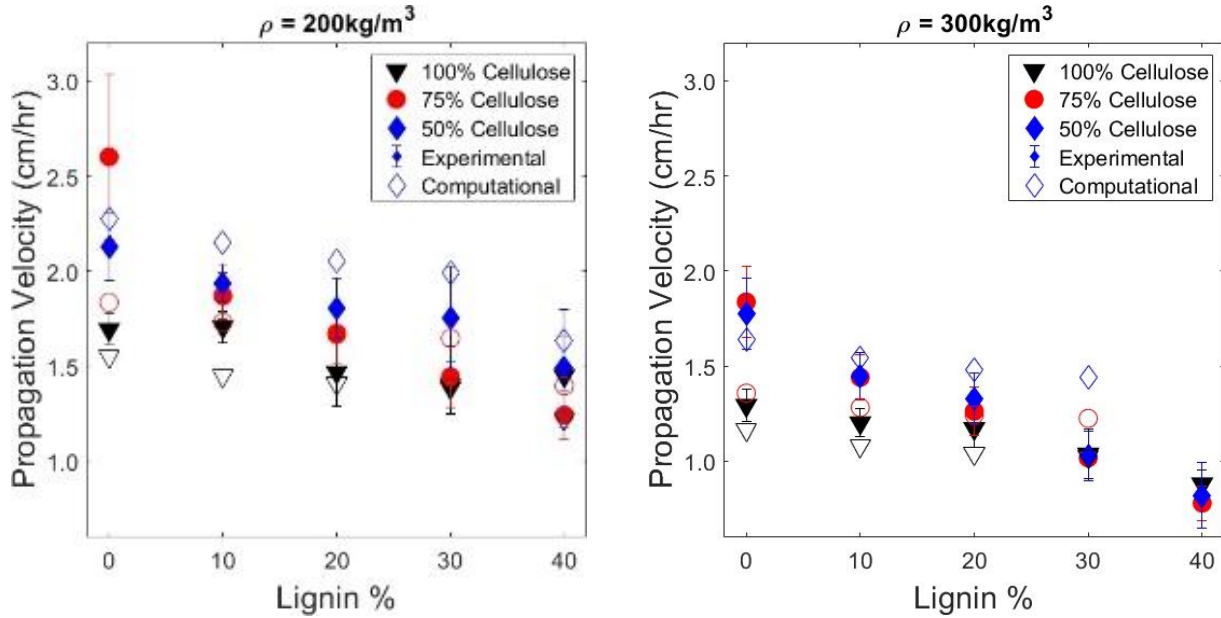


Figure 5.1.8: Experimental and computational downward smoldering propagation velocities with varying ward smoldering propagation velocities with varying lignin content at density of 200kg/m³ (left panel) and 300kg/m³(right panel).

Comparing propagation rates of fuels with 50% and 75% cellulose, there was no evidence ($p=0.79$) of a difference between them. This indicates that once a certain threshold of hemicellulose is reached, increasing the amount of hemicellulose relative to cellulose does not have a significant impact on the propagation velocity. As a result, the presence of hemicellulose is a better predictor of smoldering behavior than the amount of hemicellulose when a threshold is reached. Using a multiple linear regression model with smoldering propagation velocity as a function of lignin, hemicellulose (as a binary variable), density, and lignin*hemicellulose (to account of different slopes with lignin) the propagation velocities can be estimated with $R^2_{adj}=0.84$, and all values are significant. The results are summarized in Table 5.1. It should be noted that this model is limited at lignin contents greater than 40%, as it would predict a decrease with hemicellulose at higher values of lignin.

Table 5.1: Multiple linear regression model for estimating the downward propagation velocities.

Coefficient	Estimate	Standard Error	t-value	p-value	significance code
Intercept	2.750560	0.091726	29.987	< 2e-16	***
Lignin%	-0.008953	0.001913	-4.680	7.15e-06	***
Density	-0.004957	0.000310	-15.989	< 2e-16	***
Hemicellulose	0.561879	0.054455	10.318	< 2e16	***
Lig*Hemi	-0.017104	0.002301	-7.432	1.31e-11	***

Calculations were performed at the same conditions as the experiments to gain a better understanding of the physics causing the experimental results. The results are shown in Figure 5.1.8. The calculated propagation velocities decrease with increasing lignin content, matching the trends shown in the experimental results. Additionally, more hemicellulose in the remainder of the fuel results in faster propagation velocities from the earlier pyrolysis and lower activation energy [62]. When the non-lignin portion is 100% or 50% cellulose, the decrease in propagation velocities from 0 to 30% lignin is similar for both experimental and computational propagation velocities. However, the experimental results have a much larger decrease in propagation velocity with lignin when the non-lignin portion is 75% cellulose.

Computational reaction rates are used to understand when and how fast reactions are occurring in the different constituents, which helps explain the trends in Figure 5.1.8. The left-hand plot in Figure 5.1.9 shows the reaction rates for fuels composed of 10% and 30% lignin respectively at a depth of 5 cm. The non-lignin portion for both fuels is 75% cellulose (remainder hemicellulose), and the density is 300 kg/m^3 . Of the three constituents, lignin pyrolyzes at higher temperatures and over a longer duration (temperature increases with time prior to oxidation). As a result, more heat and time are required to pyrolyze and oxidize the lignin, slowing the smoldering propagation. Unlike lignin, hemicellulose pyrolyzes at the lowest temperatures of the three constituents, as shown in Figure 5.1.9 (earlier time corresponds to lower temperatures for pyrolysis in the plot). This earlier pyrolysis allows the other fuel constituents (cellulose and lignin) to pyrolyze and oxidize more readily. This has also been observed experimentally in combinations of cellulose and hemicellulose [62].

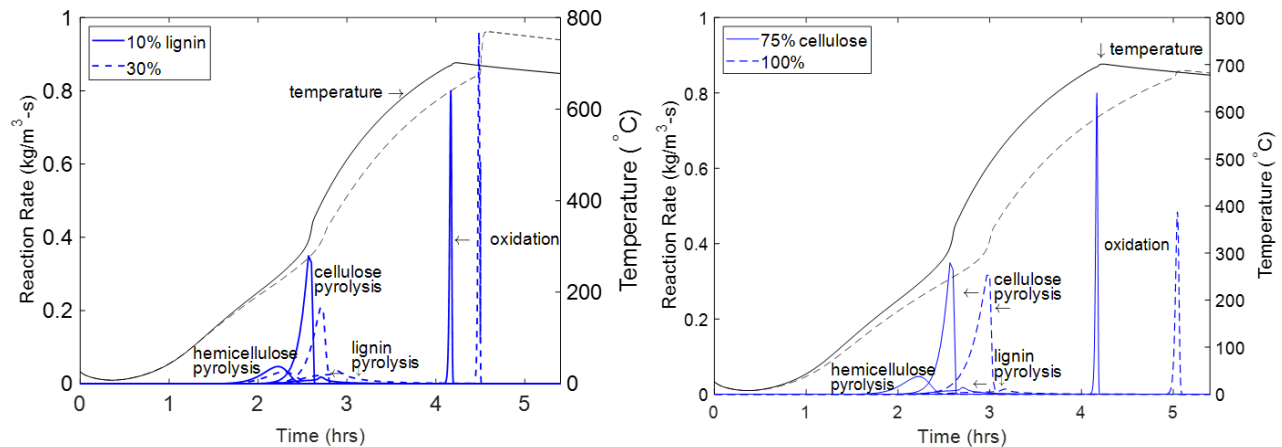


Figure 5.1.9: Computational reactions rates with at a depth of 5cm (later time corresponds to higher temperatures). The density is 300 kg/m^3 for all cases. In the plot on the left, the fuel composed 10% and 30% lignin, and the non-lignin portion of the fuel is 75% cellulose (and 25% hemicellulose). In the plot on the right, the fuel is composed of 10% lignin with remainder fuel contents of 75% and 100% cellulose. The numbers on the plot refer to the following reactions: 1. hemicellulose pyrolysis 2. cellulose pyrolysis 3. lignin pyrolysis and 4. oxidation. The oxidation for all three constituents occurs at the same time.

One possible explanation for the difference between the trends observed computationally and experimentally may be peak temperatures. Figure 5.1.10 shows the maximum temperatures, both experimental and computational, as a function of lignin content and remainder fuel content at a density of 200 kg/m^3 . These values are from the same tests shown in the left-hand

of Figure 5.1.8. Like the downward propagation velocities, the experimental peak temperatures decrease with increasing lignin content. However, the computational values do not follow this trend, as the temperature continues to increase with lignin content. Thus, it appears there are heat losses that the computational model is not capturing. These heat losses may limit the burning rate to the point where the amount of hemicellulose makes little difference in the downward propagation. Additionally, it is expected that fuels will burn faster if they reach higher temperatures all else being equal, as reaction rates increase with temperature. This is illustrated in Figure 5.1.11, which plots peak temperature vs propagation velocity for all values at a density of 200 kg/m^3 . Using a linear regression model, there is strong evidence ($p < 0.0001$) that propagation velocity tends to increase with increases in peak temperatures, although there is a notable amount of scatter ($R^2 = 0.35$). Thus, it is expected that additional heat losses will decrease propagation rates. Since lignin burns slower than cellulose and hemicellulose, there is more total heat lost to the surroundings.

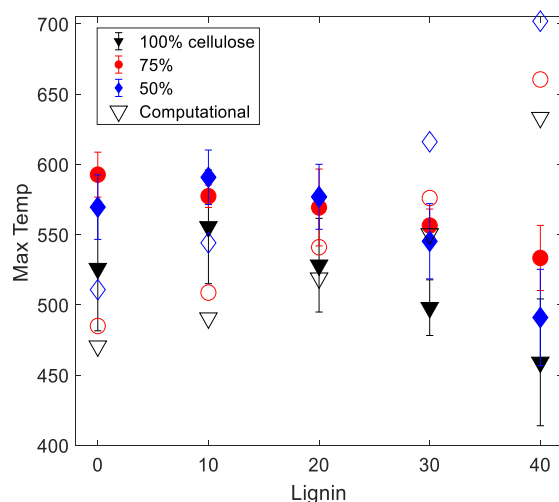


Figure 5.1.10: Experimental and computational mean peak temperatures at varying lignin contents for all three non-lignin fuel portions.

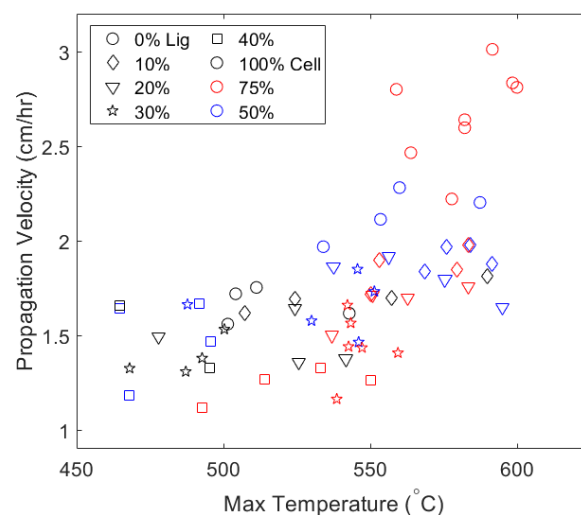


Figure 5.1.11: Peak temperatures and downward propagation rates for all samples with a density of 200 kg/m^3 .

We further investigated the effect of fuel composition on smoldering in terms of downward propagation speeds and peak temperatures computationally. A greater range of conditions was able to be evaluated computationally. We varied the fuel composition in intervals of 10% for each constituent at a density of 300 kg/m^3 , considering many possible combinations of cellulose, hemicellulose, and lignin. Figures 5.1.12 and 5.1.13 show the results for propagation speed and peak temperature, respectively.

Propagation speed decreases with increasing lignin content, while it rises with increasing hemicellulose content. However, if the hemicellulose content is kept constant, increasing lignin content decreases the speed (up to around 30% of that associated with lignin), and further increasing the lignin content slightly increases the propagation speed. We further investigated the reasons behind why increasing lignin content decreases the propagation speed and increasing hemicellulose content increases the propagation speed.

Figure 5.1.14 shows reaction rates of the fuel components for a mixture with 45% cellulose, 45% hemicellulose and 10% lignin; hemicellulose undergoes pyrolysis first and lignin last. So, larger

concentrations of hemicellulose lead to earlier mass loss, and the fuel shrinks faster, providing earlier access to oxygen and thus resulting in faster propagation. If the lignin content increases, the rate of pyrolysis drops, leading to decreases in speed. If the hemicellulose content is not changing for a particular composition, the changes in lignin and cellulose reactions need further attention.

Figure 5.1.12 shows that the peak temperature increases with increases in both hemicellulose and lignin content. We investigated the reasons for this temperature sensitivity by individually varying the physical parameters of each constituent. Figure 5.1.15 shows the resulting temperature profiles along with temperature profiles of 67.5% cellulose with 10% lignin and 22.5% hemicellulose, and 90% cellulose with 10% lignin at a density of 300 kg/m^3 . The peak temperature of 67.5% cellulose with 10% lignin and 22.5% hemicellulose closely matches that of 90% cellulose with 10% lignin when γ (the empirical parameter for radiation across pores) associated with hemicellulose matches that of ash from pure cellulose.

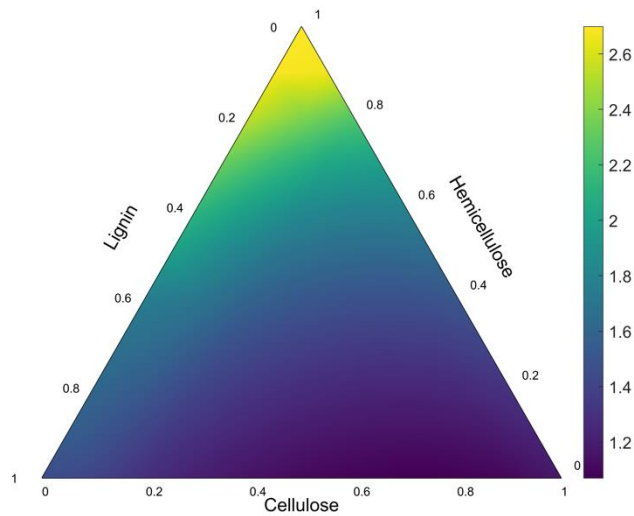


Figure 5.1.12. Propagation speeds (cm/h) for mixtures of cellulose, hemicellulose, and lignin.

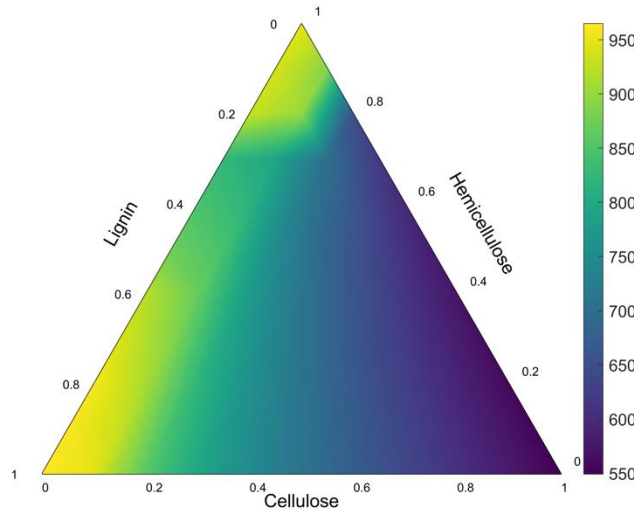


Figure 5.1.13. Peak temperatures ($^{\circ}\text{C}$) for mixtures of cellulose, hemicellulose, and lignin.

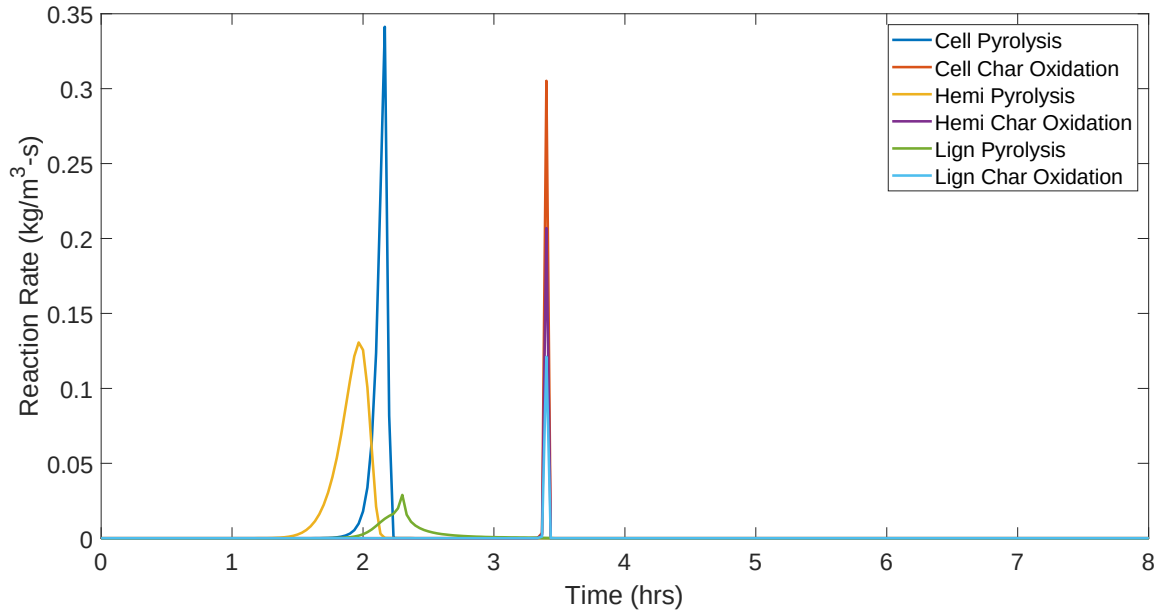


Figure 5.1.14. Reaction rates of cellulose, hemicellulose and lignin for pyrolysis and oxidation for 45% cellulose, 45% hemicellulose, and 10% lignin at density 300 kg/m³.

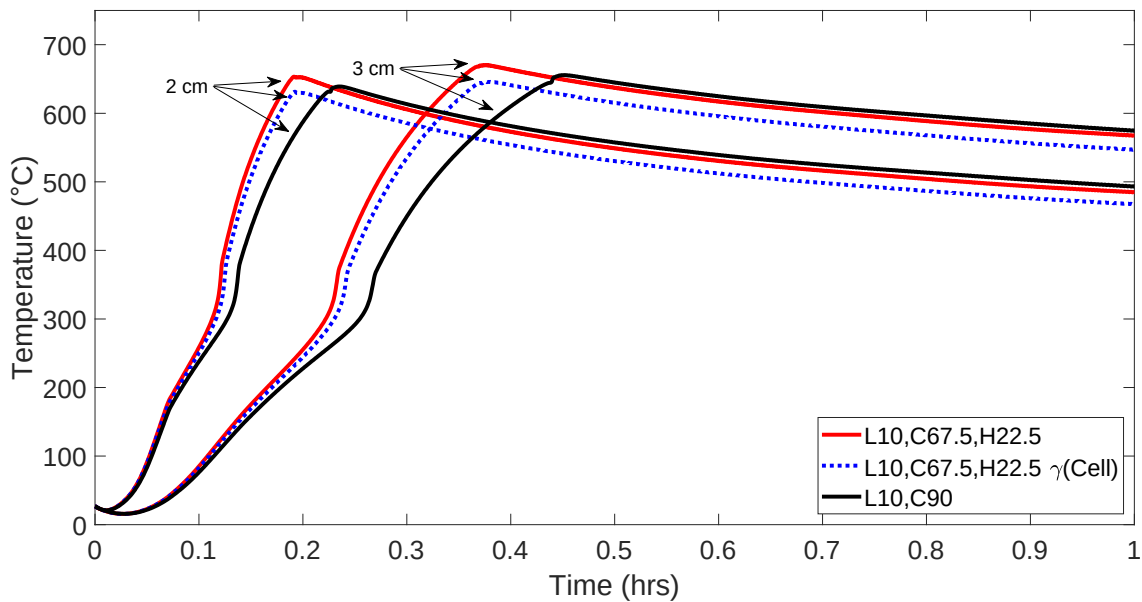


Figure 5.1.15. Temperature profiles at depths of 2 and 3 cm for fuels with density 300 kg/m³ and composition of 67.5% cellulose, 90% cellulose, and 67.5% cellulose with the empirical parameter for radiation across pores (γ) of ash coming hemicellulose set equal to cellulose.

Figure 5.1.16 shows the resulting temperature profiles along with temperature profiles of 70% cellulose with 30% lignin and 100% cellulose. The peak temperature of 70% cellulose with 30% lignin closely matches that of 100% cellulose when γ from lignin matches that of ash from pure cellulose. At 0–10% of cellulose, the temperature drops when lignin content is in the range of 20–50% (remainder is hemicellulose). The cause of this sensitivity needs further investigation.

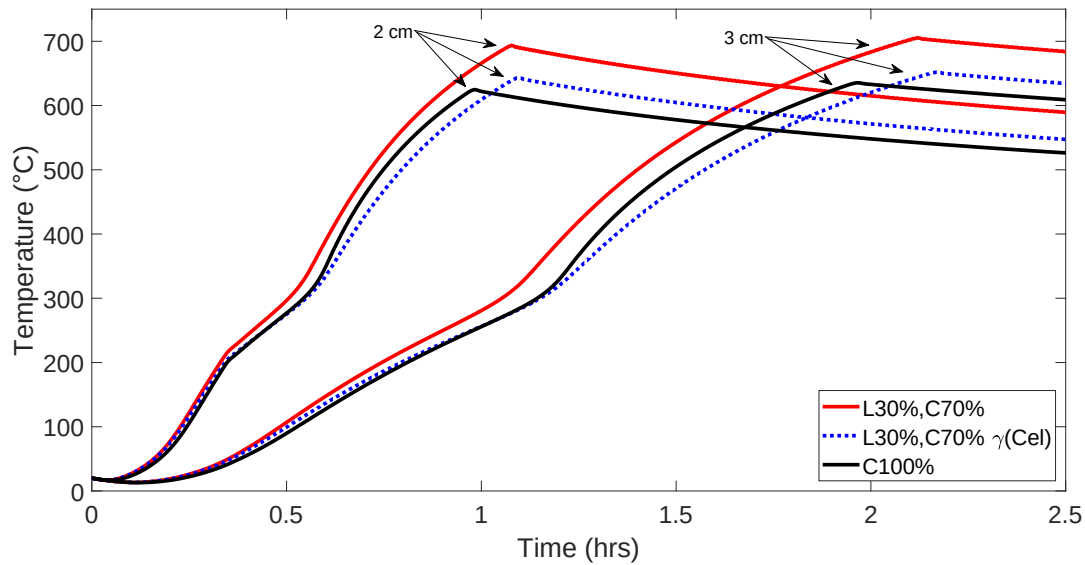


Figure 5.1.16 Temperature profiles at depth 2 and 3 cm for fuels with density 300 kg/m³ and fuel composition of 70% cellulose, 100% cellulose, and 70% cellulose with the empirical parameter for radiation across pores of ash coming hemicellulose set equal to cellulose.

5.1.4 Influence of Lignin Content on Horizontal Propagation

Additional tests were performed to determine the horizontal propagation rates at varying lignin contents. The density and content of the non-lignin components of the fuel were held constant. Determining horizontal propagation rates is necessary because there are differences in the physics controlling horizontal and downward smoldering propagation [23]. The resulting propagation rates are shown in Figure 5.1.17. Each point is the average propagation velocity from three tests. Three trends are noted. First, when the non-lignin portion is 75% or 50% cellulose (residual fuel is hemicellulose), the propagation velocity decreases roughly linearly with increasing lignin content from about 6.0 cm/hr at 0% lignin to 4.2 cm/hr at 30%. Second, for the case with 100% cellulose in the non-lignin portion of the fuel, the propagation velocity increases by about 20% as the lignin content increases from 0% to 20%.

The propagation velocity drops slightly when lignin increases from 20% to 30% lignin. Third, at lignin contents at or above 20%, the content of the non-lignin portion of the fuel makes relatively little difference in the propagation rates, as the 100%, 75%, and 50% cellulose cases all have propagation velocities that agree within 10%.

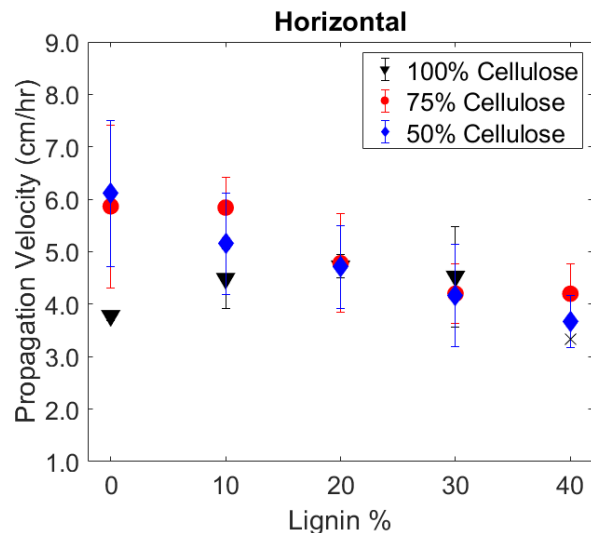


Figure 5.1.17: Experimental horizontal propagation velocities with varying lignin content for three fuel contents in the non-lignin portion. The density was 200kg/m³.

For the cases that have hemicellulose, the decrease in propagation velocity with increasing lignin content is caused by the slower reaction rates and higher activation energy of the lignin. These trends are similar to the trends with downward propagation velocities shown in Figure 5.1.8. When there is 100% cellulose in the residual fuel, the propagation velocities increase slightly with increasing lignin content (at least from 0 to 20% lignin). This occurs despite the downward propagation velocities decreasing lignin content when the remainder is 100% cellulose (see Figure 5.1.8) and cellulose having faster reaction rates than lignin (Figure 5.1.9).

The increase in velocity may also be due to structural effects. Cellulose has longer fibers that can bind together. When the fuel shrinks as the smoldering front propagates, it can create cracks in the fuel that slow the horizontal smoldering spread. An example of such cracks is shown in Figure 5.1.18. Having some lignin causes those cracks to become smaller and more distributed. Visual images were used to look at cracks in the surface for two cases: 100% cellulose and 80% cellulose/20% lignin. Comparing the 100% cellulose/0%lignin case to the 80%cellulose/20% lignin case, there were about twice as many large (<2 mm across) cracks, and the cracks were three times as long. Additionally, the cracks occurred further from the pyrolysis front, inhibiting heat transfer to unburned fuel.



Figure 5.1.18: Images for burns with 100% cellulose (right) and 80% cellulose/20%lignin (left). Numerous large, dark cracks are visible outside the burned area in the 100% cellulose case.

5.1.5 Efficacy of Surrogates of Cellulose, Hemicellulose, and Lignin to Mimic Smoldering of Natural Fuels

Table 5.1.2 shows the mean horizontal propagation for both of the natural fuels and their surrogates. The mean propagation rates of the Douglas-fir and its surrogate agree within 3% and are well within the uncertainty of each other. This suggests that the surrogate is capturing most of the horizontal smoldering behavior of the fuel. Admittedly, more testing is needed to reduce the error. For the wheat straw, the mean horizontal spread rate for the surrogate is about 10% less than that of the natural fuel, although the error is relatively large. For further comparison, some of the tests in Figure 5.1.8 had the same lignin content (20%) and organic bulk density (200kg/m^2) and similar values of cellulose (40-60%) and hemicellulose (20-40%) as wheat and its surrogate. However, inorganic content is significantly lower at >1%. The resulting horizontal propagation velocities are about 4.8cm/h, notably smaller than those of wheat and its surrogate. This observation indicates that the higher inorganic content in the wheat straw and its surrogate increases the horizontal propagation velocity. The increase in horizontal smoldering with increasing inorganic content may be driven by the higher thermal conductivity in inorganic material than organic material. Other studies have found a decrease in propagation in horizontal spread with increasing inorganic content [95], but that was over a much larger range of inorganic contents (2.5% to 40%).

Table 5.1.2: Mean horizontal propagation rates for the natural fuels and their surrogates. The error reported is uncertainty of the mean with 95% confidence.

Fuel	Mean Velocity (cm/hr)	No. tests
Wheat Straw	6.996±0.381	5
WS Surrogate	6.348±0.842	3
Douglas-Fir	3.847±0.574	3
DF surrogate	3.738±0.242	3

The mean downward propagation velocity and peak temperature for the 6 burns with Douglas-fir are shown Table 5.1.3. The corresponding velocities for the surrogate are interpolated from downward propagation values for fuels composed of 20% and 30% with non-lignin portions of 50% and 75% cellulose at 200 and 300kg/m^3 (a total of 8 conditions). The downward propagation velocities agree within 5% of each other. Although neither mean value is within the error bars of the other, there is substantial overlap in the error bars, indicating that differences between the two are minimal. Additionally, if the lignin content was 25% instead of 27% (the range of lignin content from 3 tests was 24-29%), the interpolated estimate increases to 1.255cm/h, so small differences may be due to variations in lignin content. The downward propagation values for wheat straw are not included because wheat straw failed to burn down to 6 cm. This will be further discussed shortly.

The overall downward smoldering behavior is similar for Douglas-fir and its surrogate based on measured temperature distribution. Figure 5.1.19 shows time-dependent temperature profiles at varying depths for burns with Douglas-fir as a surrogate. The surrogate is based on results from Figure 5.1.8, and as such has a slightly different fuel composition (30% lignin, 52.5% cellulose, 17.5% hemicellulose) and density (300kg/m^2). Although the estimated mean peak temperature of the surrogate is about 70°C

Table 5.1.3: Downward propagation velocities and mean peak temperatures for Douglas-fir and for a surrogate. The error reported is uncertainty in the mean with 95% confidence. The surrogate values interpolated from 8 values based on density, lignin content, and cellulose content in non-lignin portion.

Fuel	Mean Velocity (cm/hr)	Mean Peak Temp ($^\circ\text{C}$)
Douglas-Fir	1.265 ± 0.051	481.5 ± 20.3
DF Surrogate (interpolation)	1.206 ± 0.044	550.0 ± 17.2

greater than that of the Douglas-fir (see Table 5.1.3), the temperature dependence with respect to time at a given thermocouple location is similar for both natural and surrogate fuels until they reach about 450°C . After 450°C , the temperatures for the Douglas fir level off before peaking at around 480°C , whereas the surrogate continues to increase in temperature until it peaks around 550°C . The temperature profiles are roughly parallel between 100 and 400°C , so the propagation velocities are close to constant with depth in both the Douglas-fir and the surrogate fuels.

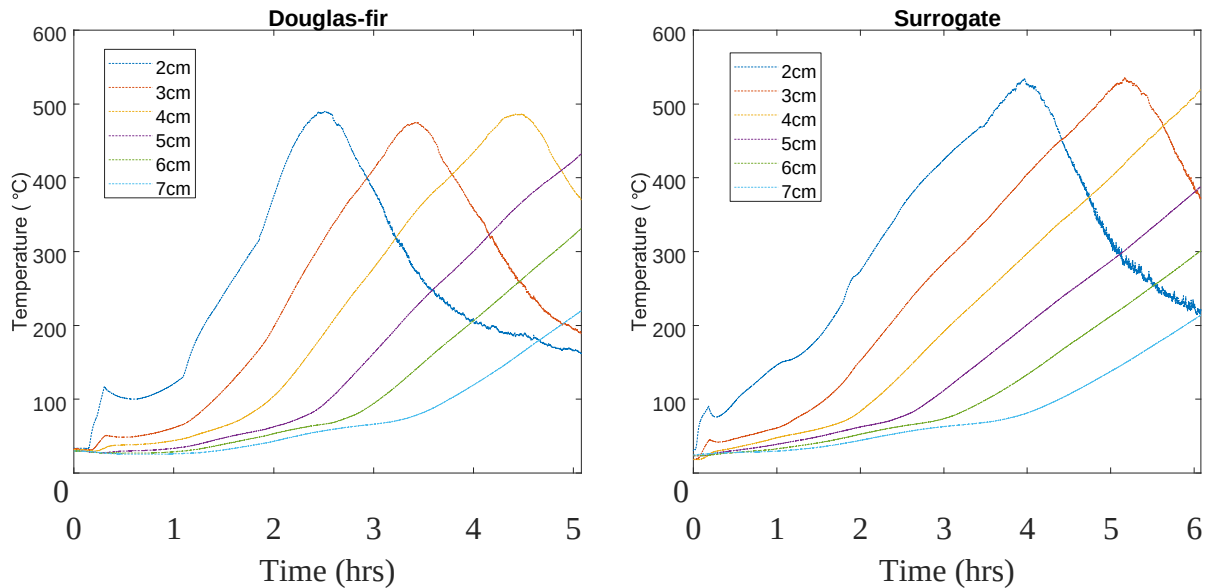


Figure 5.1.19: Temperature profiles with burning time for Douglas-fir and a surrogate. The surrogate is composed of 30% lignin, 52.5% cellulose, and 17.5% hemicellulose (75% of non-lignin portion is cellulose) and has a density of 300 kg/m^2 . Temperatures measured 1 cm below the surface are ignored due to biasing from the ignition process. Note that while the time scale is larger for the surrogate, this is balanced by the higher density.

A notable difference in the downward smoldering behavior of the wheat straw and its surrogate were observed. This difference is evident by comparing the temperature profiles in Figure 5.1.20. The wheat straw reaches a peak temperature of about 500°C at a depth of 2 cm, but the peak temperatures decay with depth. The smoldering front extinguished (i.e., failed to reach the ignition temperature) by about 6 cm below the surface. Conversely, the surrogate reaches much higher temperatures (e.g., 650°C) and shows little sign of extinguishing. The difference in downward smoldering behavior may be driven by differences in how much of the fuel was consumed. As the smoldering front propagated in the surrogate, nearly all of the organic material burned, leaving behind a layer of ash on top of the fuel. This layer reduced the oxygen availability, but also provided an insulating layer that allowed the fuel to reach temperatures greater than 600°C. Unlike the surrogate, the wheat straw failed to burn all of the organic material, indicating a lower heat release. Additionally, the unburned char and inorganic material left behind a semi-rigid structure that was much thicker than the ash layer described previously. This thicker layer severely limited the oxygen availability to the reactions zone. Any benefits from insulating effects were offset by the lower oxygen availability, resulting in extinction of the burn. Over multiple tests, the smoldering front consistently extinguished between 4 and 6 cm below the top surface of the fuel.

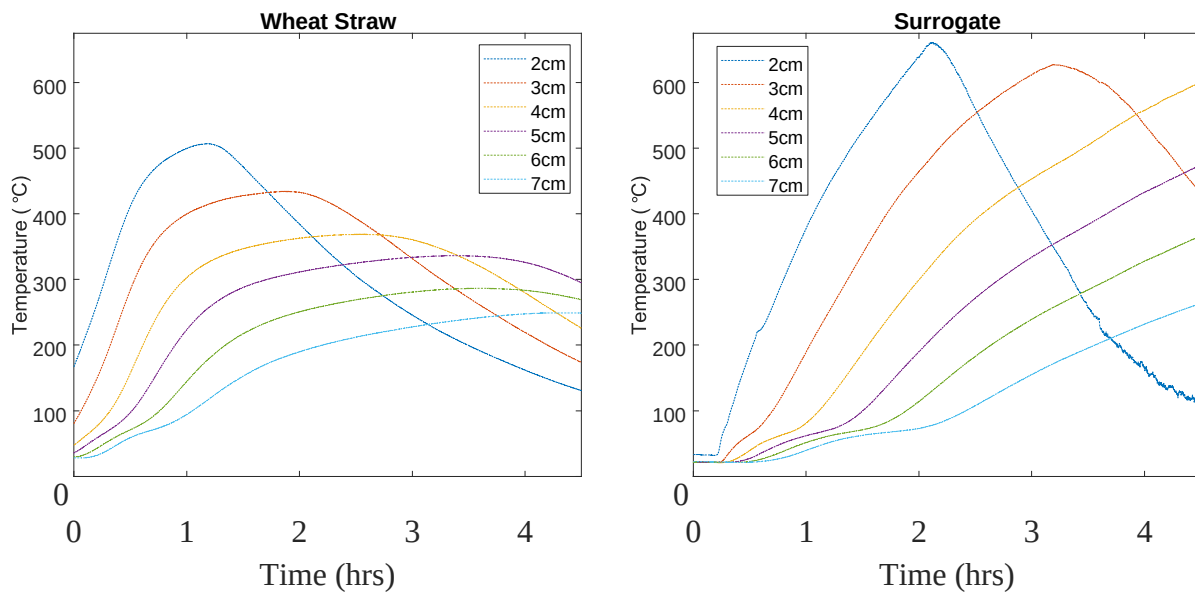


Figure 5.1.20: Temperature profiles relative to burning time for wheat straw and its surrogate. The thermocouple 1 cm below the surface is ignored due to biasing from the ignition process.

5.2 Influence of Physical Characteristics of Fuels on Smoldering

5.2.1. Particle Size, Porosity, and Permeability

5.2.1.1 Smoldering Behavior

Initial testing utilized the standard ignition protocol (i.e., heater increased from $> 370^{\circ}\text{C}$ to 500°C), and resulted in the smoldering ignition map shown in Figure 5.2.1. The experiments were conducted 6 or more times for each condition. If flaming occurred during ignition, the flames were gently smothered to allow the burning to be controlled by smoldering. It was found that particle sizes with $d < 0.85$ mm consistently ignited and transitioned to self-sustained horizontal smoldering, whereas particle sizes $d > 1.27$ mm were unable to transition to self-sustained smoldering. For particles with $0.85 < d < 1.27$ mm, in 60% of tests the fuel was able to sustain smoldering. The results illustrated in Figure 5.2.1 affirm a sensitivity of sustained smoldering to the size of particles, as expected. Moreover, smaller particles are more prone to sustain horizontal smoldering, at least within the range of particles evaluated.

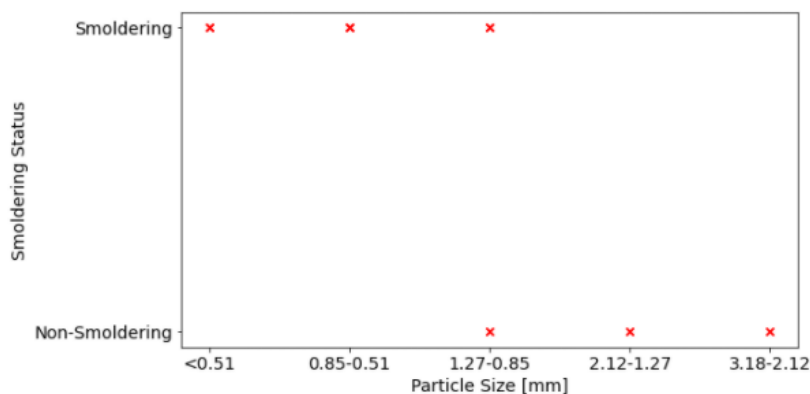


Figure 5.2.1: Particle sizes that resulted in sustained smoldering or non-smoldering.

The experiments were repeated, but with the higher temperature ignition protocol (i.e., heater inserted at a temperature $> 750^{\circ}\text{C}$ and regulated at 800°C to 850°C). These experiments were performed to determine if ignition using greater heat transfer would allow the larger particle size samples to burn, either through flaming or smoldering combustion. All particle size samples ignited by flaming combustion with the higher temperature heater. The flames were not quenched, and the burn was allowed to progress naturally. The burning of samples with particles $d > 1.27\text{mm}$ ultimately completely quenched while particle sizes with $d < 0.85\text{mm}$ transitioned to self-sustained smoldering. These observations are notable for two reasons. First, it shows that ignition is insensitive to the particle size if the temperature is sufficiently high, at least within the sizes considered here. Second, sustained smoldering does not occur for relatively larger particle sizes, even when the ignition source is higher and the burning occurs at higher temperatures (i.e., flaming).

Further experiments were conducted with the lower temperature ignition protocol (i.e., heater was placed in contact with the fuel at room temperature and increased to $345^{\circ}\text{C} \pm 25^{\circ}\text{C}$) to investigate if a slower heating process influenced ignition and smoldering behavior. The rationale for the experiments was that the more gradual heating approach would reduce char build up around the heater (i.e., because the fuel would experience pyrolysis) and reduce the

possibility of initiation by flaming combustion. Without flames, the heat transfer to the virgin fuel would be reduced. The results of self-sustained smoldering or non-ignition matched those observed using the standard ignition protocol (see Figure 5.2.1). The significance of these findings is that ignition to self-sustained horizontal smoldering was not affected by the heating (i.e., ignition) process as long as the peak temperature of the heater had enough energy to initiate self-sustained smoldering.

Horizontal smoldering spread rates were quantified to further understand the sensitivities of smoldering behavior to particle sizes. Results for the 3 ignition approaches are reported in Figure 5.2.2; in some instances, the data overlaps. Smoldering propagation rates decrease as particle sizes increase, despite the density of the fuel bed being reduced with larger particles. Ryu et al., [40] found similar smoldering characteristics while studying the smoldering combustion of multiple biomass fuels exposed to forced flow. They found that smaller particles have increased burning rates and ignition front speeds, when investigating particles with characteristic diameters of $4\text{ mm} < d < 35\text{ cm}$. This sensitivity was attributed to larger particles being thermally thicker than smaller particles, slowing the devolatilization rates while having increased distributed heat transfer to nearby particles. In this work, no inherent difference in spread rates is noted between the different ignition protocols once smoldering was established. This shows that with sufficient time smoldering behavior becomes independent of the ignition source. It is noted that despite having reduced porosity and permeability (i.e., reduced oxygen availability), horizontal smoldering propagated faster through smaller particles. This suggests that the smoldering behavior is dominated by heat transfer and the thermal thickness of the fuel. Smaller particles have more contact area with adjacent particles, increasing the relative conductive heat transfer from one particle to another. Additionally, smaller particles compared to larger particles have less surface area exposed to air, resulting in less heat loss due to convection within the system. The net heat transfer characteristics results in heat transfer occurring more readily between smaller particles; hence these particles have an increased smoldering propagation rate compared to larger particles. This logic is further evaluated using a simplified heat transfer model and evaluating the thermal thickness, as described later.

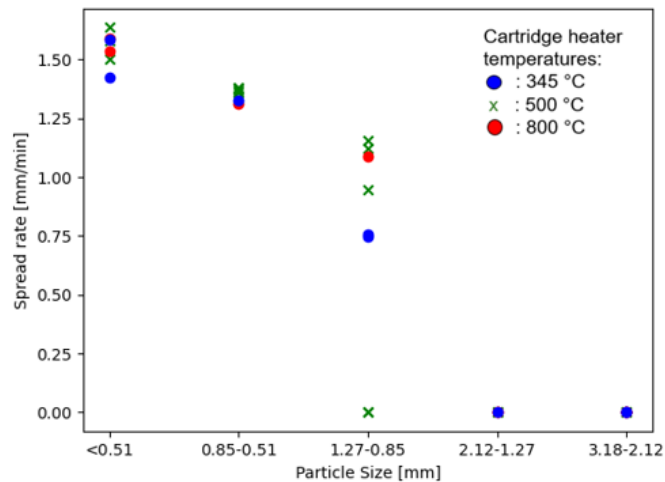


Figure 5.2.2: Plot comparing smoldering spread rates relative to particle sizes.

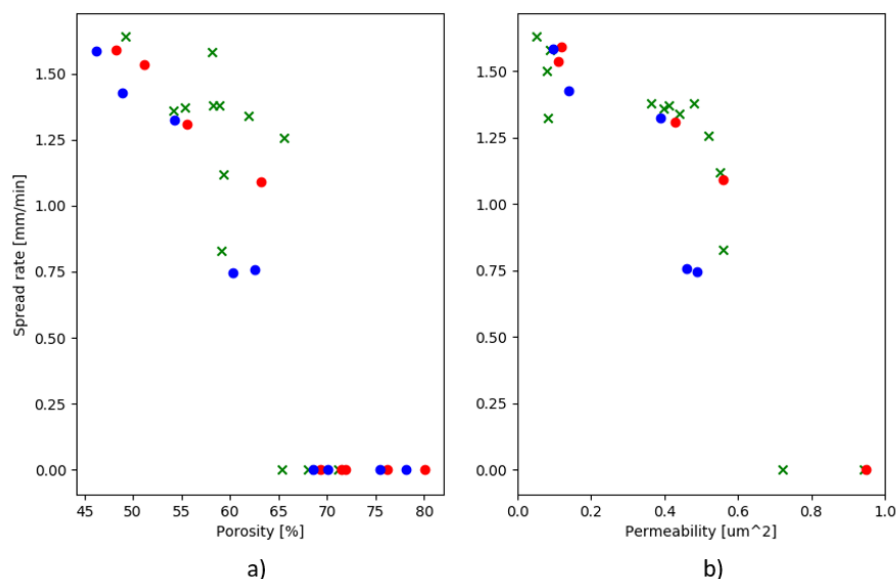


Figure 5.2.3: The horizontal spread rate relative to porosity (a) and permeability (b) of samples.

In an effort to better understand the influence of oxygen availability on smoldering behavior through porous beds the smoldering spread rates are plotted relative to the measured porosity, as shown in Figure 5.2.3a. Samples with porosity values over 65% were not able to transition to self-sustained smoldering. Additionally, samples with lower porosity values had an increased smoldering propagation rate compared to samples at higher porosity. To further evaluate the sensitivity of smoldering to oxygen availability, the smoldering rate is reported relative to the permeability, as shown in Figure 5.2.3b. Considering the influence of the permeability of a porous media on smoldering behavior is important because highly porous material may not be very permeable to air as discussed earlier. In general, samples with lower permeability had increased smoldering propagation rates. Note that air can more readily reach the reaction zone for fuels with increased permeability. However, the results in Figure 5.2.3b indicate that fuels with lower porosities have increased spread rate. This characteristic was consistent throughout all ignition protocols.

The observation that smoldering propagates faster through smaller particles, despite having reduced porosity and permeability (i.e., reduced oxygen availability), further supports the concept that the smoldering behavior through porous media of the size studied here is dominated by heat transfer.

It is noted that the smoldering behavior just described is for smoldering along the surface. Arguably, the oxygen availability may be sufficient in the region of the fuel near the surface, where the burning occurred in this study.

Testing was conducted to investigate the effect of mixing smaller particle sizes with larger particle sizes, as shown in Table 5.2. Mixtures of particles with varying characteristic sizes is more consistent with those expected in naturally occurring fuels. It was hypothesized that mixtures would more readily sustain smoldering because smaller particle sizes would fill void space between larger particles, decreasing the resistance to heat transfer. Combining 50% (by weight) of particle size <0.85 mm with 50% of particle sizes in the range of $1.27 < d < 2.12$ mm

allowed the larger particle size sample to sustain smoldering. Recall that the fuel bed with just particle sizes $1.27 < d < 2.12$ mm did not smolder. Further evaluating the role of mixtures, when 50% (by weight) of particle sizes < 0.85 mm was mixed with 50% of particle sizes in the range of $2.12 < d < 3.18$ mm, the sample was unable to propagate to self-sustained smoldering. However, by increasing the mixture to 75% of particle size < 0.85 mm and 25% of particle sizes in the range of $2.12 < d < 3.18$, the mixture sample was able to transition to self-sustained smoldering. In summary, smaller particles within mixtures can facilitate self-sustained smoldering among larger particles that are not prone to burn.

Experiments were conducted to measure the downward propagation rates to further understand the influence of heat transfer and oxygen availability on smoldering behavior through small particles. Three downward tests were conducted for each range of particle sizes and propagation rates were quantified. Particles of size $d < 0.51$ mm and $0.51 \text{ mm} < d < 0.85$ mm had downward propagation rates of 0.151 mm/min and 0.096 mm/min on average, respectively (see Table 5.2). All particles of size $d > 0.85$ did not transition to self-sustained smoldering in the downward tests. The qualitative trends of the downward smoldering behavior (i.e., sustained smoldering and relative propagation rates) are similar to those observed in horizontal smoldering experiments. Specifically, as particle size decreases the smoldering propagation rate and propensity to smolder increase. It is noted that downward smoldering propagation rates are an order of magnitude smaller than horizontal spread rates. This difference between horizontal and downward smoldering propagation rates of the same fuel are consistent with experiments of other fuels found in literature [75]. The results from the downward experiments are consistent with the hypothesis that differences in heat transfer characteristics dominate changes in smoldering behavior within the range of particle sizes evaluated. It is expected, however, that reduced oxygen availability becomes more significant based on the reduced downward propagation rates compared to horizontal spread rates.

Table 5.2: Mixtures of particles that were burned and the resulting (or lack thereof) self-sustained horizontal smoldering and average downward smoldering propagation rates for different homogenous particles. Results from single particle sizes shown in Figure 5.2.1 are reported for comparison.

Mixed Horizontal Smoldering			
Particle Size A [mm]	wt%	Particle Size B [mm]	wt%
3.18 > d > 2.12	100	N/A	N/A
2.12 > d > 1.27	100	N/A	N/A
1.27 > d > 0.85	100	N/A	N/A
0.85 > d > 0.51	100	N/A	N/A
d < 0.51	100	N/A	N/A
3.18 > d > 2.12	50	d < 0.51	50
2.12 > d > 1.27	50	d < 0.51	50
1.27 > d > 0.85	50	d < 0.51	50
0.85 > d > 0.51	50	d < 0.51	50
3.18 > d > 2.12	75	d < 0.51	25
Downward Smoldering			
Particle Size	Downward Spread Rate [mm/min]		
3.18 > d > 2.12	Did not smolder		
2.12 > d > 1.27	Did not smolder		
1.27 > d > 0.85	Did not smolder		
0.85 > d > 0.51	0.096		
d < 0.51	0.151		
Did not Smolder:			
Self-Sustained Smoldering			

5.2.1.2 Heat Transfer Analysis of Influence of Particle Size

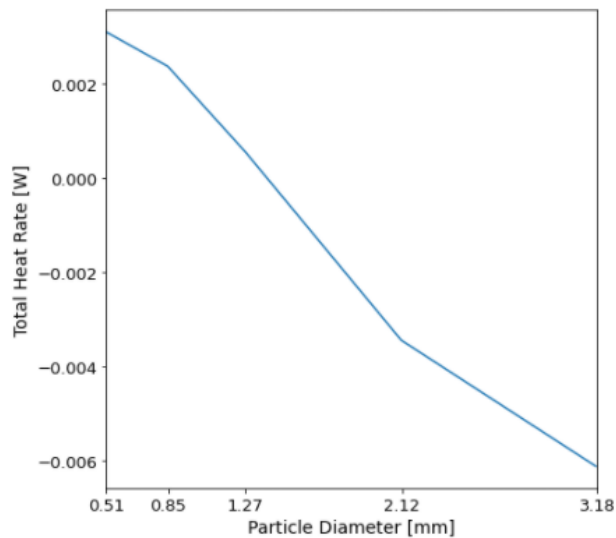


Figure 5.2.4: Estimated total heat rate from one heated particle to an adjacent particle for varying particle sizes.

Figure 5.2.4 shows an estimated total heat transfer between particles, depending on the particle sizes. The heat transfer analysis described earlier was used. The exact magnitude of the heat transfer is not as critical as the trends; specifically, heat transfer to adjacent particles decreases with increasing particle diameter. A negative heat transfer rate means that overall heat is lost because of natural convection. The trends shown in Figure 5.2.4 are consistent with findings in the experimental study described previously. Specifically, a net heat loss is predicted for particles with a $d > 1.27$ mm, consistent with the measured conditions that do not sustain smoldering. Moreover, smaller particles have faster spread rates, also consistent with greater heat transfer between particles. Anecdotally, the measured conditions that support sustained smoldering are those with calculated positive heat transfer (i.e., heat transfer between particles) while conditions that do not sustain smoldering have calculated negative heat transfer, as shown in Figure 5.2.4.

The contribution of conduction, convection and radiation heat transfer to the overall heat transfer rate are now considered to better understand sensitivities to particle sizes. Figure 5.2.5 shows the predicted heat transfer due to conduction, convection and radiation. Conduction heat transfer between particles increases with increasing particle size. Recall that conduction is controlled by an effective thermal conductivity. The greater heat transfer between larger particles occurs because of the larger surface area that can conduct heat.

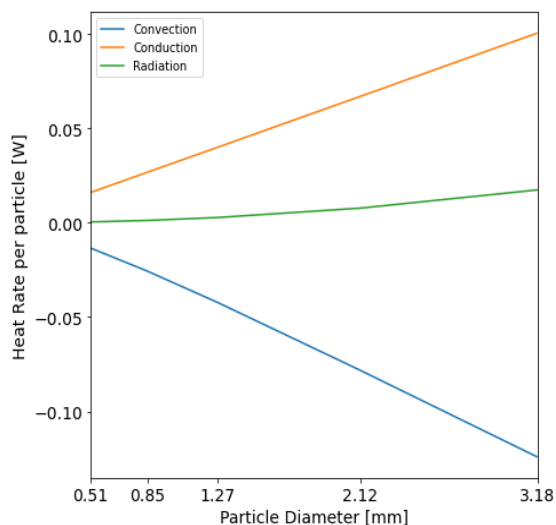


Figure 5.2.5: Heat rate contributions from conduction, convection, and radiation on the heat transfer from on heated particle to an adjacent particle for varying particle sizes.

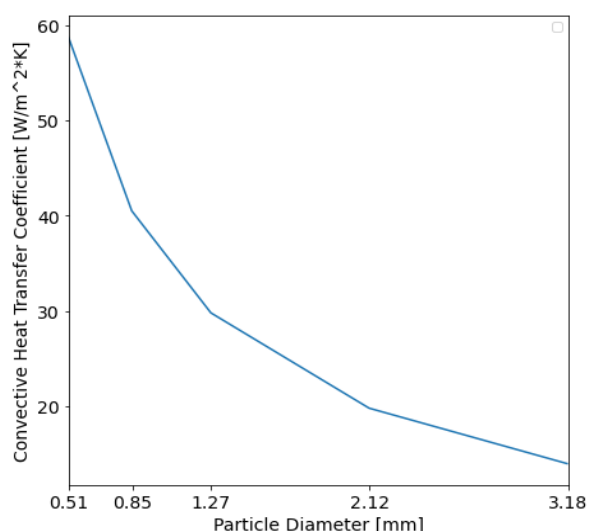


Figure 5.2.6: Convective heat transfer coefficient for varying particle sizes.

Convection heat transfer tends to remove heat between adjacent particles, as shown in Figure 5.2.5. Note that the convective heat transfer coefficient decreases with increasing particle size, as seen in Figure 5.2.6. This trend occurs because the Nu correlations are heavily dependent on the Re of flow around the particles. Smaller particle sizes have higher Re numbers because the flow area is constrained and the same bulk flow rate from natural convection is assumed. Despite the reduced convective heat transfer coefficient for larger particles, the overall convective heat transfer increases with increases in particle diameter because of the greater surface area for heat transfer. As a result, more heat is expected to be lost to surrounding air instead of being transferred to adjacent particles, as particle sizes increase.

Radiative heat transfer tends to increase as the particle size increases, as seen in Figure 5.2.5. This occurs because of the increased surface area of the larger particle compared to that of the smaller particles. However, the contribution of radiation at the low temperatures seen in smoldering is not as significant as compared to that of conduction and convection. If higher temperatures occur, such as those observed in flaming combustion, the heat rate from radiation increases significantly and will become a more dominant mode of heat transfer [96]. This can result in larger fuels under flaming combustion having higher spread rates compared to smaller fuel sizes.

The Biot number (Bi) was calculated to identify if the thermal thickness influences the results of this study. The results are consistent with heat transfer characteristics controlling smoldering behavior. Specifically, the Biot numbers for the particle sizes investigated in this study ranged from $0.0083 < Bi < 0.218$. Therefore, the larger particles investigated are more thermally thick than the smaller particles. Due to this, larger particles have slower devolatilization rates and more distributed heat transfer to adjacent particles when compared to smaller particles [40]. This leads to larger particles having decreased heat transfer rates to adjacent particles causing decreased smoldering front propagation rates.

5.2.2. Fuel Adhesion and Cracking

When the smoldering front is spreading across the surface of a fuel bed, large cracks in the fuel can inhibit smoldering spread, as shown in Figure 5.2.7. The two fuel samples have the same fuel content (75% cellulose, 25% hemicellulose) and organic bulk density (150 kg/m^3). The image on the left has 0% MC, and the image on the right has 30% MC. In the image on the right, there are several large cracks. These are not observed in the image on the left. The left-hand case had a horizontal propagation velocity of 7.0 cm/hr , compared with a propagation velocity of 3.2 cm/hr for the right-hand case. While some of this may be due simply to the heat losses caused by evaporating moisture, the large cracks inhibit conduction horizontally through the fuel, slowing the smoldering propagation.

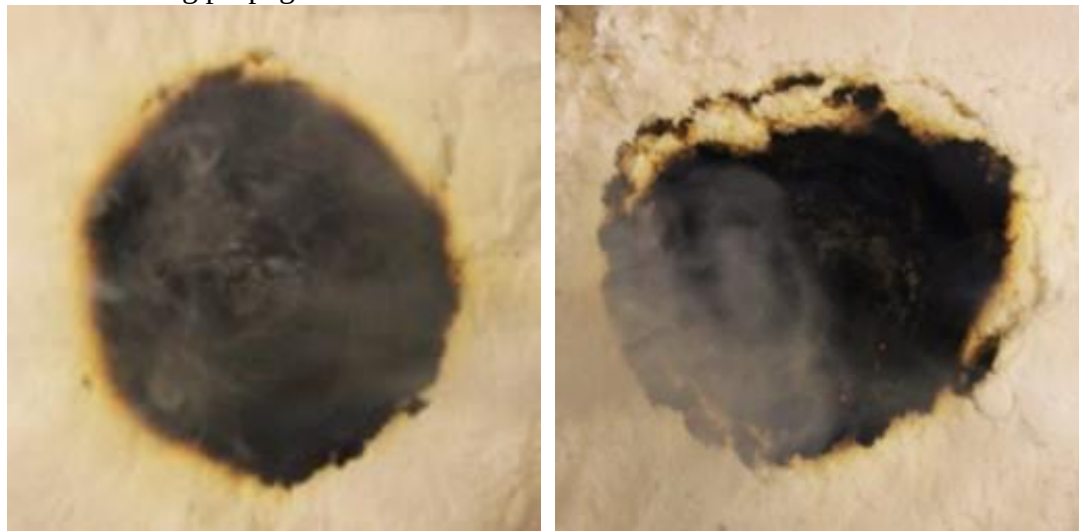


Figure 5.2.7: Images from two burns 75% cellulose (remainder hemicellulose) at 150 kg/m^3 . The sample on the left had 0% MC, and the image on the right had 30% MC. The burned region is approximately 10 cm across.

The MC was varied from 0 to 30% in samples with 100%, 75%, and 50% cellulose (remainder hemicellulose). For these tests, the organic bulk density (does not include moisture) was held constant at 150 kg/m^3 . The results are shown in Figure 5.2.8. The horizontal propagation velocities decreased with MC for all fuel contents. Additionally, the transient times (the time before the burn showed a steady state velocity) increased dramatically, from about 10 minutes at 0% MC to at least 60 minutes at 100% MC (shown in the plot on the right). Downward smoldering tests were also performed for fuels with 75% cellulose. The downward smoldering tests help establish a baseline to evaluate whether changes in propagation rates are driven by changes in burning rates or by structural changes. While there was generally a small decrease with MC (decreases by $\sim 20\%$ from 0 to 30% MC), this decrease was relatively small compared to the change in horizontal propagation velocity, illustrating that the decrease in horizontal propagation velocities is caused partially by these cracks and not just heat losses.

Further testing will be performed at these conditions to obtain more accurate values. An image processing code (currently in development) will be used to quantify the number and size of the cracks occurring in the surface of the fuel. This will allow the team to correlate cracking behavior with smoldering propagation rates. Because the imaging code requires large visual contrast between the undisturbed fuel, cracks, and burned fuel, only combinations of cellulose

and hemicellulose will be considered. Lignin is much darker than cellulose and hemicellulose, making the contrasts harder to detect. If possible, a second method of varying the fuel adhesion will also be used in addition to MC. However, an additive that can change adhesion and cracking characteristics may also induce significant fuel chemistry changes, so that will need to be taken into account. Downward and horizontal smoldering tests will be performed in combinations of cellulose and hemicellulose. The quantity of the binding agent will be varied to determine how changes in cracking behavior impact smoldering propagation.

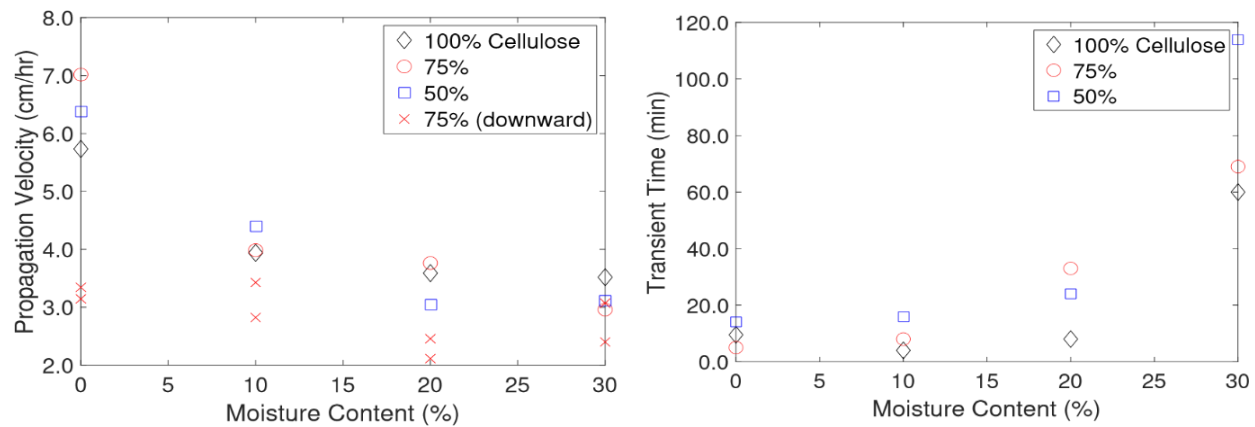


Figure 5.2.8: Propagation velocities and transient times for three fuel contents at varying moisture contents. The organic bulk density (not including moisture) was 150kg/m³. The propagation velocities are all horizontal, except for the unfilled circles, which are downward results. The transient times are the time before the propagation velocities are approximately steady-state.

5.2.3. Influence of Fuel Density on Smoldering Behavior

How the density of the fuel affects smoldering behavior was evaluated. The compositions of softwood, hardwood, and paper was selected (as given in Table 4.6.2). Then, for the three compositions, we performed simulations with varying density. Figure 5.2.9 shows that propagation speed decreases with density and peak temperature increases with increases in density. Hardwood has the highest propagation speeds, due to its higher hemicellulose content compared to the other fuels. From hardwood to softwood the propagation speed decreases

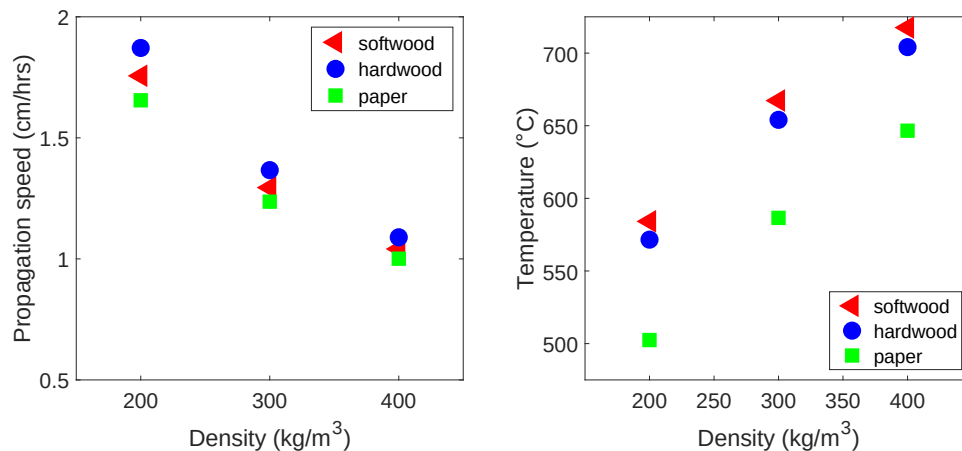


Figure 5.2.9. Effects of varying density on propagation speed (left) and peak temperature (right).

because lignin content increases. Softwood has higher peak temperatures than hardwood. Paper has the lowest propagation speeds and peak temperatures, since paper is mostly comprised of cellulose. As the density increases, the effect of composition on propagation speeds decreases to the point where they nearly match for 400 kg/m³; in contrast, composition plays an important role for peak temperature over the entire density range considered.

5.2.4. Influence of Moisture Content on Smoldering Behavior

The effect of moisture content on smoldering characteristics was considered by assessing the propagation velocities for fuels with 100% cellulose. Propagation velocity increased by 4% as moisture content increased from 0 to 30% (Figure 5.2.10). One of the reasons for this increase is that when water is mixed with the fuel, the fuel expands, which eventually leads to a reduction in density of the fuel once the water is evaporated. Above 30% moisture content there was no significant change in the propagation speed; the propagation speed dropped by about 1.5% when the moisture content was increased from 30 to 70 %. It is noted that the temperature continuously decreased as moisture content was increased from 0 to 70% as expected. This indicates that the changes associated with density have a greater influence on the smoldering speed than changes in temperature.

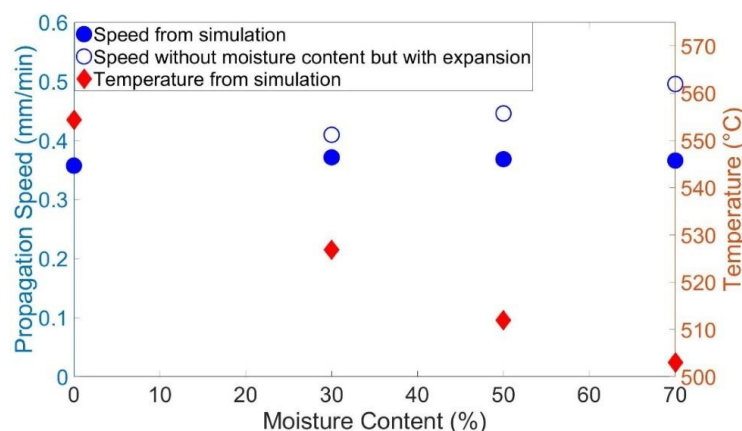


Figure 5.2.10: Propagation speed and mean peak temperature for varying moisture content along with propagation speed with expansion but without moisture content 100% cellulose.

Next, we analyzed how moisture content affects smoldering behavior for the three compositions used previously (softwood, hardwood, and paper). In this analysis we considered that the fuels do not expand with addition of water, since woody fuels do not have such reported expansion [23]. Figure 5.2.11 shows that both propagation speeds and peak temperatures decrease with increases in moisture content. Hardwood has the highest propagation speeds. Softwood and paper have very close propagation speeds, and the values become closer with increasing moisture content. The two fuels have matching propagation speeds at 70% moisture content. However, paper exhibits significantly lower peak temperatures, while softwood has the highest peak temperature. These results motivate further analysis into the reasons for these behaviors.

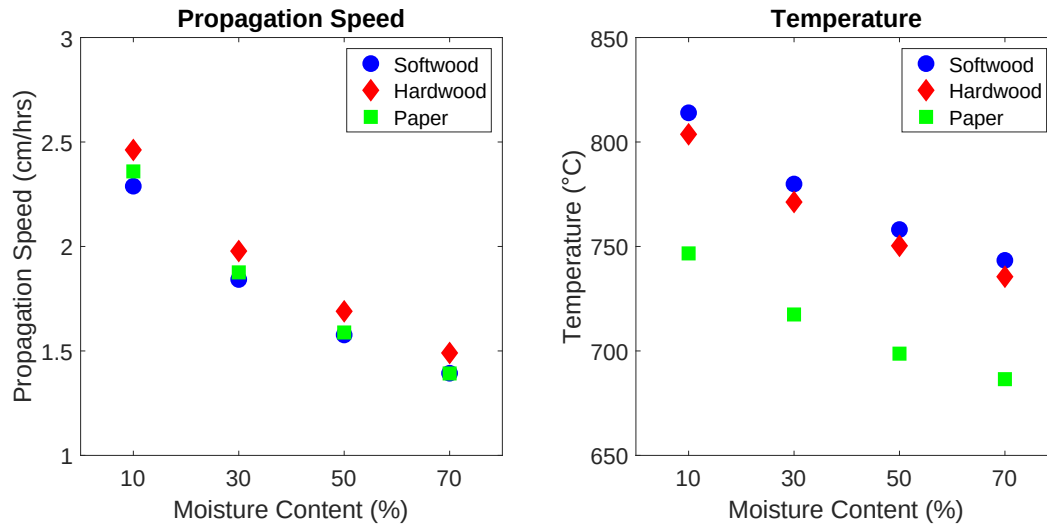


Figure 5.2.11 Effect of moisture content on propagation speeds and peak temperatures.

We also studied the interdependence between oxygen concentration and moisture content for a successful smoldering ignition, using softwood. We varied the moisture content from 10% to 110% in increments of 10%, and the oxygen concentration (Y_{O_2}) from 10% to 40% in increments of 5%. We used an increment of 1% near the boundary of the ignition and non-ignition zones to correctly identify the transition. Figure 5.2.12 shows the ignition and non-ignition zones for different oxygen concentration and moisture content combinations. We find similar behavior as Huang and Rein [97] did for peat, where increases in moisture content require increases in oxygen concentration for successful ignition. This study helps to predict a relationship for critical moisture content and critical oxygen concentration for smoldering ignition of woody fuels.

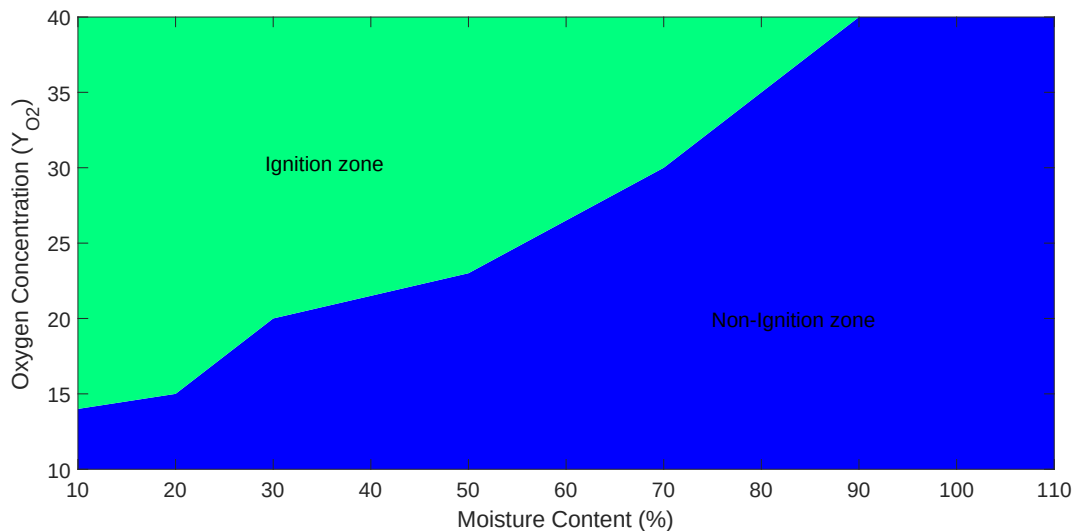


Figure 5.2.12 Effect of moisture content and oxygen concentration on ignition.

5.3 Influence of Wind

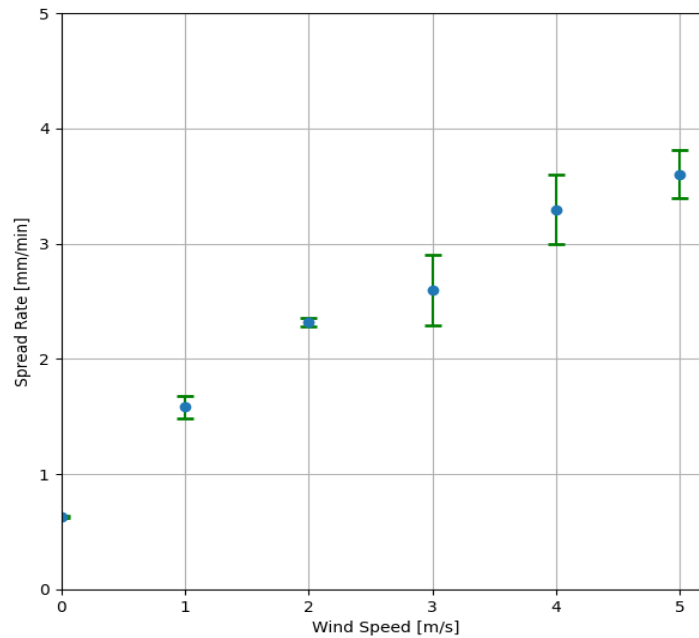


Figure 5.3.1: Plot of the spread rates at various wind speeds. Higher order uncertainty with 95% confidence is reported.

Spread rates at corresponding wind speeds are shown in Figure 5.3.1 with error bars determined from higher order uncertainty with 95% confidence. A total of 15 smoldering experiments were performed with 3 tests at each wind speed. The results indicate that spread rates increase with wind speed linearly. Additionally, the spread rate at a wind speed of 1 m/s was double the spread rate in the same fuel under windless conditions. The precision uncertainty in the spread rates were higher than those determined design stage uncertainties. This is due to difficulties in repeatability of smoldering experiments in addition to the nature of smoldering front progression, which will be discussed in more detail later. It is noted that the spread rates determined were subsurface spread rates at 0.013 m below the surface.

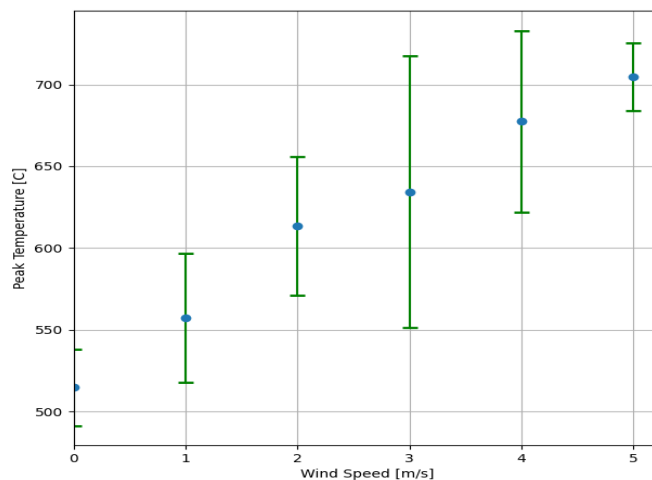


Figure 5.3.2: Plot of the peak temperatures at various wind speeds. Higher order uncertainty with 95% confidence is reported.

Peak temperatures corresponding to wind speeds are shown in Figure 5.3.2 with error bars determined through a higher order uncertainty. It was found that smoldering peak temperatures increase with wind speed. Additionally, during experiments it was observed that the intensity of the glowing smoldering front increased with wind speed. This is thought to be due to the increased oxygen concentration to the reaction zone. Additionally, the wind may reduce the heat losses due to moisture evaporation through the blowing effect of hot gasses coming off the fuel bed [13].

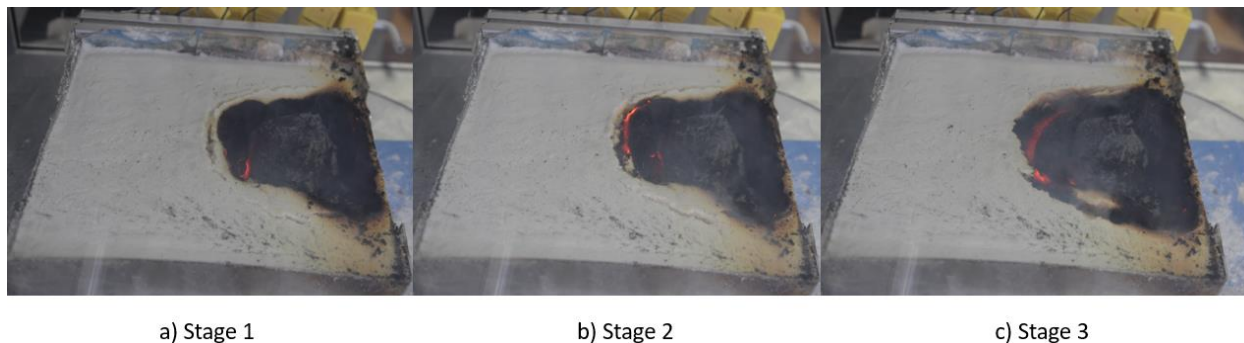


Figure 5.3.4: Visual images taken during a smoldering test at a wind speed of 3 m/s showing the various stages of the smoldering front progression.

During the experiments it was observed that the smoldering front progressed in 3 stages. First, fuel ahead of the smoldering front began to crack due to fuel shrinkage creating a gap in the fuel, as seen in Figure 5.3.4a. Second, the smoldering front progressed over and/or around the crack until the smoldering front was over the cracked section of the fuel, as seen in Figure 5.3.4b. Third, once the smoldering front was over the cracked portion of the fuel, the smoldering front progressed downward until reaching the bottom of the reactor box, as seen in Figure 5.3.4c. Once the fuel was cracked and the downward smoldering began, the smoldering front of the fuel was unable to progress horizontally until another crack in front of the smoldering front formed. This process was repeated until the smoldering front reached the edge of the reactor box and was extinguished.

5.4 Smoldering Behavior of Field Burns and Samples (Objectives 5 and 7)

5.4.1 Propagation rates of smoldering burns

Table 5.4.1 shows the results from the field study portion of the project. The propagation rates from the field samples and the field burns with respect to moisture indicate that the data from the two groups does not follow the same trend (Figure 5.4.1). The field burns had a larger moisture content range (31% to 76%) but the propagation rate remained less than 1 mm/min (0.12 to 0.67 mm/min), while the laboratory burns (of field samples) had moisture contents of 15% or less but a large range of propagation rates (0.36 to 3.69 mm/min). This implies that the moisture content may not have as significant an influence on propagation rates.

The propagation rate for the field samples and the field burns with respect to bulk density is shown in Figure 5.4.2. The field burns had a larger bulk density range (74 to 193 kg/m³) but the propagation rate remained less than 1 mm/min (0.12 to 0.67 mm/min), while the field sample burns had densities less than 110 kg/m³ (88 to 107 kg/m³) but a larger range of propagation rates (0.36 to 3.69 mm/min). Additional field studies should be performed prior to drawing conclusions.

Table 5.4.1: Data for the field samples and field burns.

ID	Location	Moisture (%)	Bulk density (kg/m ³)	Mean Edge Temperature (°C)	Mean Propagation Rate (mm/min)
Field Burn 5	Winthrop, WA	55%	74	282	0.67
Field Burn 6	Winthrop, WA	31%	193	251	0.12
Field Burn 7	Winthrop, WA	76%	121	277	0.65
Sample Burn 1	Sisters, OR	15%	98	250	0.36
Sample Burn 2	Sisters, OR	9%	107	287	1.16
Sample Burn 3	Sisters, OR	13%	103	255	0.36
Sample Burn 4	Silverlake, OR	11%	88	301	3.69
Sample Burn 5	Silverlake, OR	14%	106	292	1.99

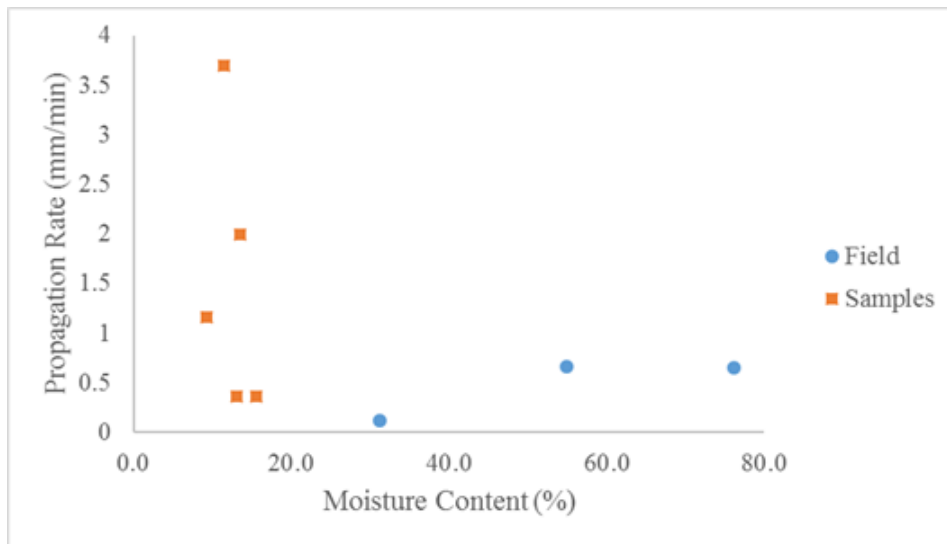


Figure 5.4.1: The horizontal propagation rate relative to the moisture content.

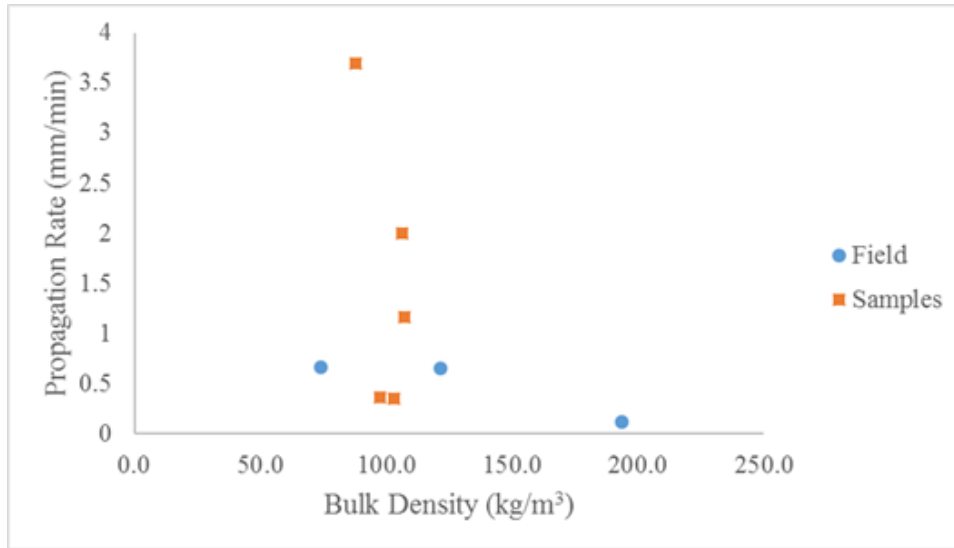


Figure 5.4.2: The horizontal propagation rate versus bulks density.

The mean propagation rate with respect to the smoldering front's mean edge temperature (Figure 5.4.3) shows that the propagation rate increases as temperature increases. At 301°C the propagation rate is 30 times greater than at 251°C.

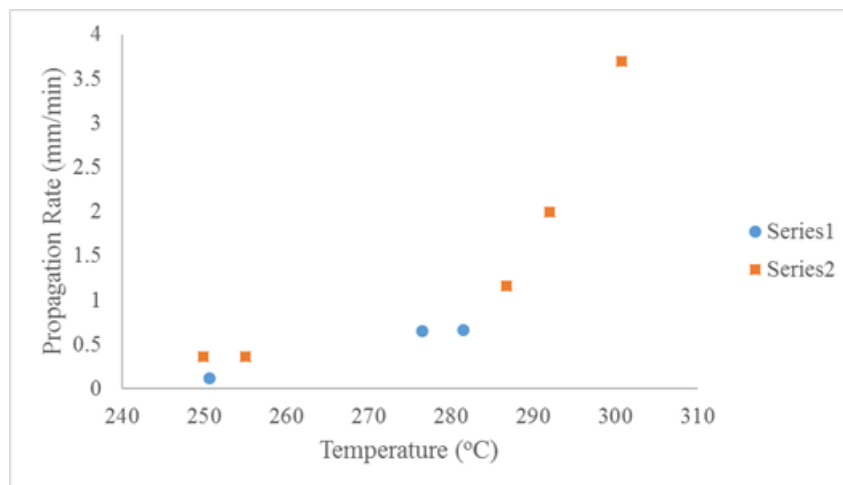


Figure 5.4.3: The horizontal propagation rate versus mean edge temperature.

5.4.2 Gaseous Emissions from Smoldering Front

Emission factors for the five burns were tabulated as the result of integrating the samples taken over the smoldering phase (Table 5.4.2). MCE was 0.81 for each of the three-point source duff burns (single tree burns). MCE was 0.85 and 0.86 for the two prescribed fires, indicating more of a mix of flaming and smoldering emissions. The CO₂ emission factors are lower and the CO emission factors are higher for the single tree burns, indicating less efficient (more smoldering) combustion for the point source ignition. The hydrocarbon emission factors overall were more varied, with overlapping ranges between the two ignition types.

Table 5.4.2: Emission Factors (g emission/ kg fuel consumed) of CH₄, C₂ - C₆ compounds, from the two large scale plots and the three-point source single tree sites.

Ignition Type Site Date	Flame front Winthrop #1 6/5/2017	Flame front Goat #6 6/7/2017	Point Source 8 Mile #1 6/27/2017	Point Source 8 Mile #2 6/28/2017	Point Source 8 Mile #3 6/29/2017
MCE	0.86	0.87	0.81	0.81	0.81
CO	165	149	213	216	216
CO ₂	1546	1572	1452	1472	1453
CH ₄	5.63	4.89	8.32	4.07	7.50
C ₂ H ₆	0.88	1.17	1.88	0.84	1.64
C ₂ H ₄	1.16	0.86	1.62	0.80	1.33
C ₂ H ₂	0.05	0.00	0.04	0.01	0.02
C ₃ H ₈	0.50	0.40	0.85	0.43	0.78
C ₃ H ₆	0.89	0.78	1.45	0.68	1.20
C ₃ H ₄	0.00	0.00	0.01	0.00	0.00
isobutane	0.03	0.09	0.09	0.05	0.08
butane	0.14	0.18	0.29	0.16	0.26
trans-2 butene	0.09	0.08	0.12	0.05	0.10
butene	0.18	0.16	0.31	0.14	0.25
isobutene	0.20	0.21	0.37	0.17	0.30
cis-2 butene	0.07	0.05	0.10	0.04	0.08
1,3- butadiene	0.04	0.03	0.13	0.04	0.07
isopentane	0.02	0.04	0.04	0.02	0.04
pentane	0.07	0.09	0.15	0.09	0.15
cis-2 pentene	0.03	0.04	0.04	0.02	0.03
1-pentene	0.10	0.08	0.16	0.07	0.12
trans-2 pentene	0.02	0.01	0.03	0.01	0.02
hexane	0.01	0.00	0.10	0.06	0.09

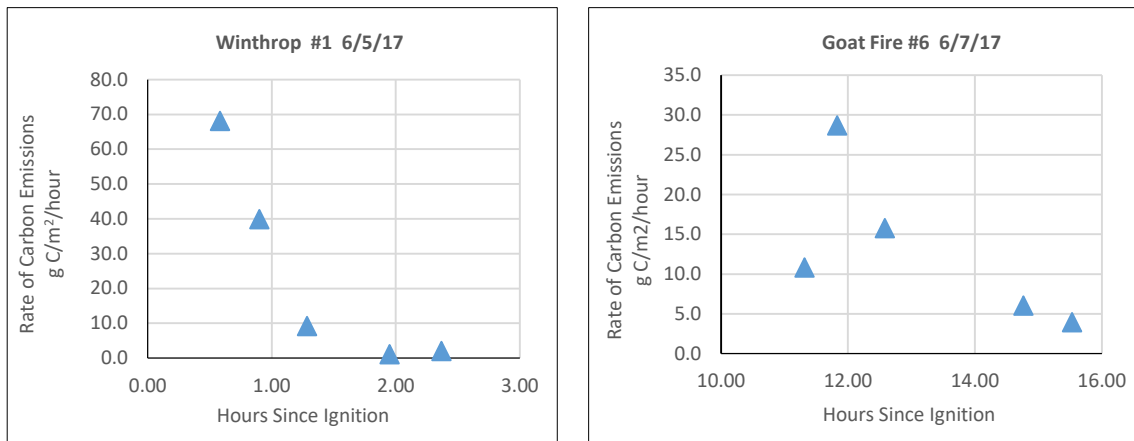


Figure 5.4.4: Rate of carbon emissions (g C/ m²/hr.) for the two prescribed fire flame front ignition plots.

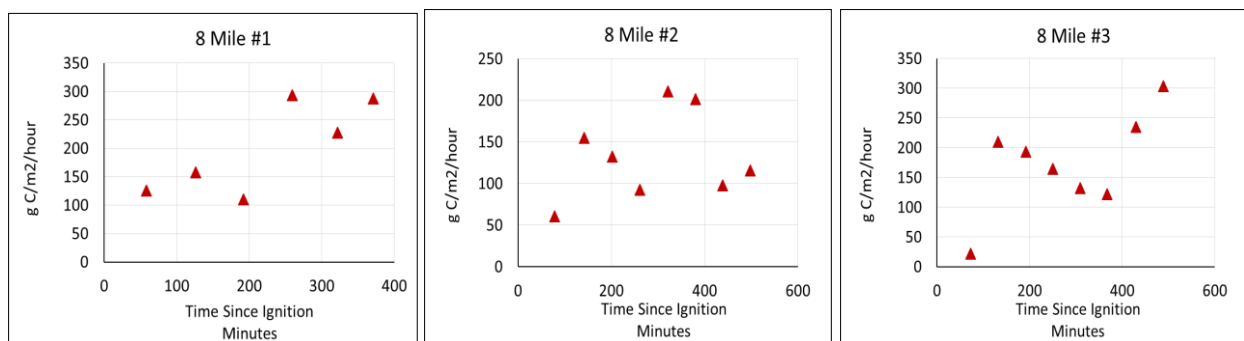


Figure 5.4.5: Rate of carbon release (g C/m²/hr.) for the 3 single tree duff burn experiments where a point was ignited in the center of the plot.

The rate of carbon emissions from the two prescribed burns displays a pattern of exponential decline over time as the duff was consumed (Figure 5.4.4). The Winthrop site emitted carbon at a rate of 70 g/m²/ hour one half hour after ignition when smoldering was active, but declined sharply over the next hour. The Goat #6 fire was not sampled until the morning after an evening ignition. The single tree sites had much higher carbon emission rates (Figure 5.4.5), and followed a different pattern over time as emissions increased with growth of the radius of the smoldering area in a less continuous pattern (Figure 5.4.5).

5.5 Sensitivities of Smoldering Ignition (objectives 1 and 3)

5.5.1 Minimum heat flux for ignition

We used simulations to identify the minimum heat flux required for ignition, for the fuels described in Table 5.5.1. To determine this, we set an external heat flux on the upper boundary and applied it for the full simulation time of 15 hours. We varied the magnitude of this external heat flux using increments of 0.1 kW/m². For this study we considered the selected eight fuel types. For these fuels, we found minimum heat flux for ignition ranging over 7–8.8 kW/m², as shown in Table 5.5.1. Paper, comprised mostly of cellulose, ignites with the lowest heat flux, while twigs, comprised of over 50% hemicellulose, require the highest heat flux to ignite. Of the fuels considered, peat and duff have the most lignin, and ignite with moderate heat fluxes.

Table 5.5.1. Minimum heat flux ($Q_{\min}$) for ignition for eight fuels.

Fuel	$Q_{\min}(\text{kW/m}^2)$
Paper	7
Softwood	7.6
Hardwood	7.8
Pine needles	7.8
Grass blend	7.8
Peat	7.9
Duff	7.9
Twigs	8.8

Thus, it appears that the composition correlates to minimum heat flux required for ignition. We postulate that activation energy for oxidation of the fuel (E_f) drives this minimum heat flux. If the heat flux is lower than $Q_{\min}$, the fuel does not ignite because the heat input is insufficient to initiate oxidation reactions. The activation energy for oxidation is 278 kJ/mol for cellulose, 289 kJ/mol for lignin, and 294 kJ/mol for hemicellulose. Since cellulose has lowest activation energy, it will ignite at lower heat fluxes, while hemicellulose needs higher heat fluxes to overcome its higher activation energy.

5.5.2 Heat flux and exposure time for ignition

Next, we varied the external heat flux and found the corresponding minimum exposure time required for ignition. We define the required exposure time as the minimum time required to achieve self-sustained smoldering ignition for a given applied heat flux. Figure 5.5.1 shows the eight different heat flux to exposure time plots for the fuels. As one might expect, as the external heat flux increases the required exposure time for ignition decreases, though in a nonlinear fashion. Initially, increases in heat flux past the minimum value lead to sharp drops in the required exposure time, but with further increases in heat flux past approximately 12 kW/m² the exposure time levels off.

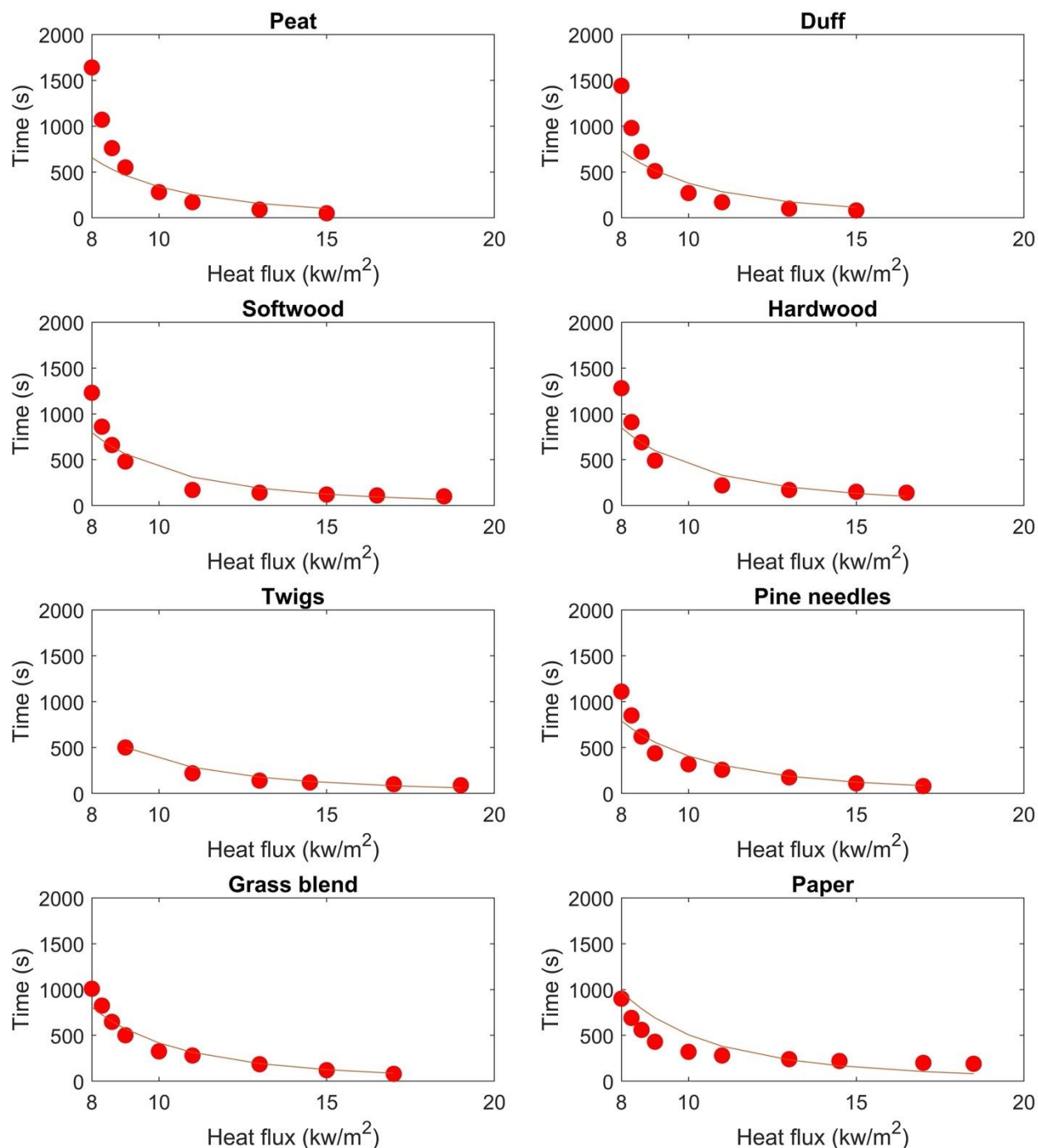


Figure 5.5.1. Minimum exposure time for ignition with varying heat flux for the fuels considered. Note that the horizontal axes (abscissa) do not start at zero.

Next, we investigated what drives the variations in exposure time. Figure 5.5.2 shows the reaction rates for duff smoldering with a heat flux of 8 kW/m². At the surface, the oxidation reactions begin at 1440 s, which coincides with the minimum exposure time necessary to ignite. Thus, the heat-flux exposure time is the ignition time of the fuel and char. The heat produced from oxidation is enough to overcome the heat required for endothermic processes (heat losses, pyrolysis, and drying) and smoldering front to propagate without an external heat flux. The total

heat produced by oxidation is 10.65 MJ, while the combined convective and radiative losses together with the heat required for pyrolysis and drying are 1.86 MJ. Thus, the heat produced from oxidation reactions overcomes the heat required for endothermic processes and enables smoldering propagation.

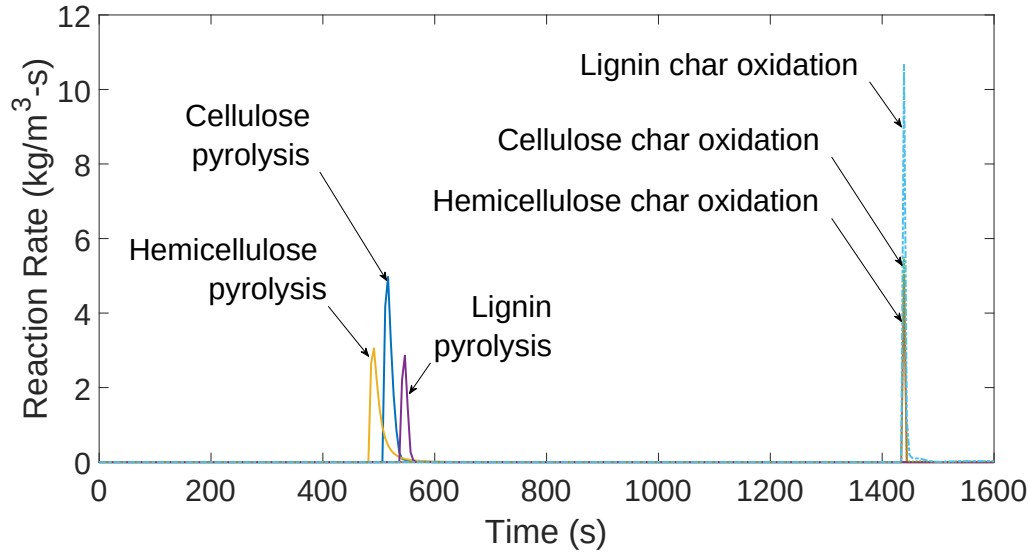


Figure 5.5.2. Reaction rates of cellulose, hemicellulose, and lignin for pyrolysis and oxidation for duff at the surface.

Figure 5.5.1 shows the relationship between minimum heat flux and exposure time changes for different fuels, showing that fuel composition plays a role in smoldering ignition. To model how exposure time and heat flux quantitatively scale with the fuel composition, we performed a linear regression of the data using the Matlab function regress, where the independent variables are mass fraction of cellulose ($Y_{\text{cellulose}}$), mass fraction of hemicellulose ($Y_{\text{hemicellulose}}$), mass fraction of lignin (Y_{lignin}), and radiant heat flux (Q , in kW/m^2) and the dependent variable is exposure time (t , in s). The resulting relationship is,

$$t = 3.42 \times 10^5 \frac{Y_{\text{cellulose}}^{0.0717} \times Y_{\text{hemicellulose}}^{0.0384}}{Y_{\text{lignin}}^{0.1723} \times Q^{2.9619}},$$

with a goodness of fit (R^2) value of 0.8086, indicating reasonable agreement but that more test cases may be required for a better fit. Figure 5.5.1 also shows the fit for each fuel, based on the associated composition. There is a strong inverse relationship between heat flux and exposure time. The dependence on composition is weaker, but with a relatively larger (inverse) dependence on lignin, because lignin has a higher char yield resulting in greater heat release.

5.5.3 Effect of Moisture Content on Ignition

Next, we investigated the effect of moisture content on ignition because the moisture content in fuel beds may vary due to weather conditions. Figure 5.5.3 shows that when moisture content increases from 10% to 30% for duff and hardwood, the minimum exposure time for ignition for a given heat flux increases. However, the two fuels exhibit different increases in exposure time for the same increase in moisture content; for example, at higher heat fluxes ($13\text{--}15 \text{ kW/m}^2$) the exposure time increases by 104% for duff and by 153% for hardwood. This coupling between moisture content and composition warrants further investigation.

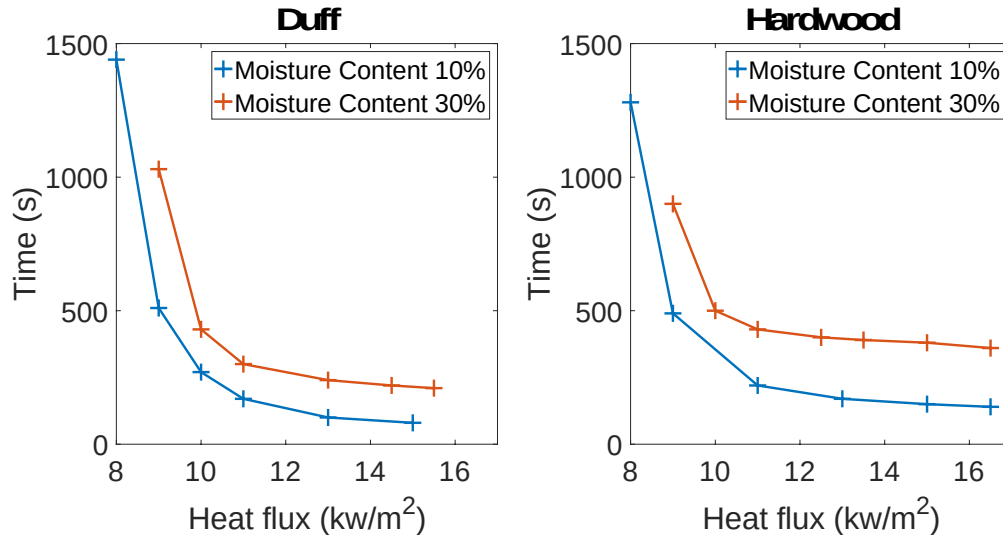


Figure 5.5.3. Minimum exposure time for ignition with varying applied heat flux for duff and hardwood at moisture contents of 10% and 30%.

5.5.3 Smoldering ignition by Conduction

Finally, we extended the model to investigate how a hot metal particle affects smoldering ignition when it comes into contact with the surface of the fuel bed at a particular temperature. To analyze this, we geometrically created a layer of the metal on top of the sample in the one-dimensional domain. We assigned an initial temperature to the metal layer, and then the boundary conditions at the interface and bottom match those used previously: exposed to the open atmosphere with heat and mass transfer, and some heat transfer at the bottom, respectively. Since this is a one-dimensional model there are limitations associated with replicating real-life scenarios, and so this approach may not completely replicate a smoldering ignition by a hot particle dropped into a fuel bed.

We identified a particular smoldering ignition temperature for a particular thickness of the metal layer. Then, we varied the thickness of the metal layer and identified that the ignition temperature changes with the thickness of the metal. We further searched for a relationship between the thickness of the metal and the ignition temperature. We varied the thickness of the metal from 1 mm to 10 mm and identified an ignition temperature for each thickness. The corresponding temperatures are captured by changing the temperature with a step size of 10 °C. These ignition temperatures change with the type of the fuel, so we performed the simulations for the same eight fuel types. For the initial study we used Aluminum 1100 as the metal, then to analyze the effect of the type of the metal we repeated the study for steel 302/304.

To investigate the relationship between ignition temperature and the thickness of the metal layer, we varied the thickness of the aluminum layer at the top of the fuel bed from 1 mm to 10 mm for the eight different fuel beds. Each fuel exhibits a different response to increasing metal layer thickness, where ignition temperature decreases non-linearly with the thickness of the metal. Figure 5.5.4 shows how ignition temperature varies with metal thickness for the eight fuels. These results agree with those of Urban et al. [12], who show similar trends in ignition temperature with varying particle diameter in their experimental study. Assuming the particle diameter to be proportional to the thickness of metal layer in the one-dimensional

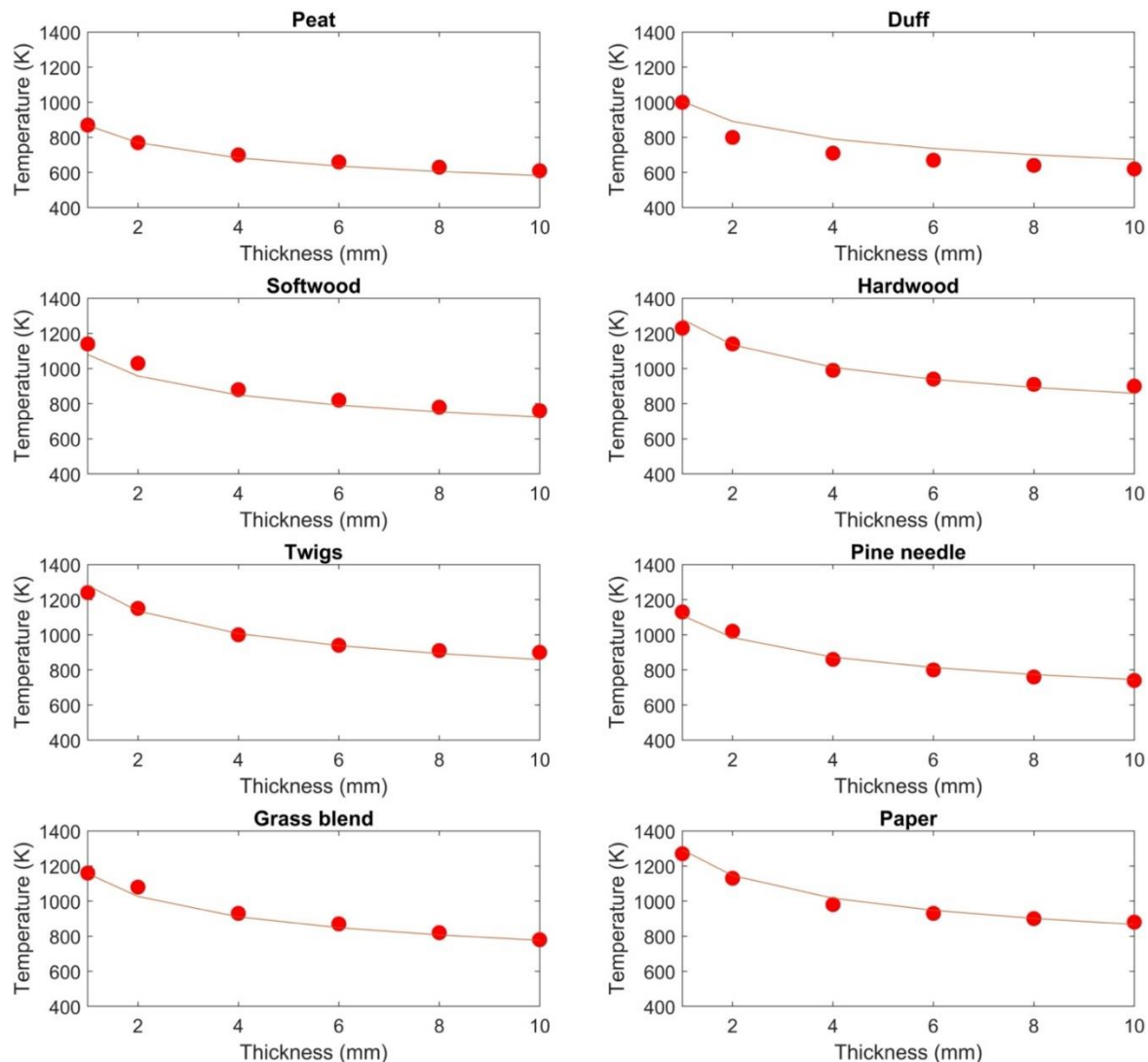


Figure 5.5.4. Ignition temperatures with varying metal layer thickness for eight fuel beds.

domain in the computational setup, the results fall in similar temperature ranges when we compare the grass blend plots. However, they performed the experiments under a wind velocity of 0.5 m/s, and furthermore did not mention the specific composition of the grass blend used. These discrepancies could help explain the differences observed with our results. The focus of our study is to understand how fuel composition affects hot particle ignition together with the particle size, which is not addressed in their work.

Next, we investigated what drives the variations in ignition temperatures for different fuels. We saw that the overall thermal conductivity of the fuel mixture plays the predominant role when it comes to igniting the sample. The thermal conductivities of cellulose, hemicellulose, and lignin are 0.356, 0.34, and 0.39 W/(mK), respectively. We calculated an overall thermal conductivity for a fuel mixture using the composition of the mixture and the above individual thermal conductivity values. Ignition temperature increases with decreases in the overall thermal conductivity. Table 5.5.2 shows the overall thermal conductivity of each fuel with ignition temperature at 1 mm metal thickness.

Table 5.5.2. Thermal conductivity of each fuel, and ignition temperature at 1 mm thick metal layer.

Fuel	Thermal conductivity (W/(m K))	Ignition temperature (K)
Peat	0.3755	870
Duff	0.3671	1000
Pine needles	0.3621	1130
Softwood	0.3620	1140
Grass blend	0.3607	1160
Hardwood	0.3580	1230
Twigs	0.3579	1240
Paper	0.3570	1270

We further investigated the effect of thermal conductivity by artificially creating a fuel mixture with the composition of paper, but which has the overall thermal conductivity of duff. This fuel retained all other physical and kinetic parameters of paper. Figure 5.5.5 shows that the ignition temperatures of this modified paper fuel drop and approach the temperatures of duff. This confirms that the overall thermal conductivity of the fuel mixture is the driving force of fuel samples having different ignition temperatures.

This finding shows that thermal conductivity drives smoldering ignition via conduction, while activation energy is the primary factor limiting/controlling ignition via radiation. This implies that chemical kinetics drive the ignition via radiation, while physical properties drive ignition from conduction. Thus, fuels with varying physical and chemical characteristics will behave differently under different ignition sources.

Figure 5.5.5 shows the relationship between ignition temperature and thickness of the metal layer. The results show that the fuel composition plays a role in smoldering ignition in conjunction with the thickness of the metal layer. To model how ignition temperature and thickness of the metal layer quantitatively scale with the fuel composition, we performed a linear regression of the data using the Matlab function regress(), where the independent variables are mass fraction of cellulose ($Y_{\text{cellulose}}$), mass fraction of hemicellulose ($Y_{\text{hemicellulose}}$), mass fraction of lignin (Y_{lignin}), and thickness of the metal layer (Δt , in mm) and the dependent variable is ignition temperature (T , in K). The resulting relationship is

$$T = 489.9 \frac{Y_{\text{hemicellulose}}^{0.1116}}{Y_{\text{cellulose}}^{0.4809} \times Y_{\text{lignin}}^{0.4530} \times \Delta t^{0.1732}}$$

with a goodness of fit (R^2) value of 0.9493, indicating a good agreement. Figure 5.5.4 also shows the fit as curves in each plot for each fuel, based on the associated composition. There is a weaker inverse relationship with thickness of the metal. There are relatively strong inverse relationships with cellulose and lignin, and a weak direct relationship with hemicellulose.

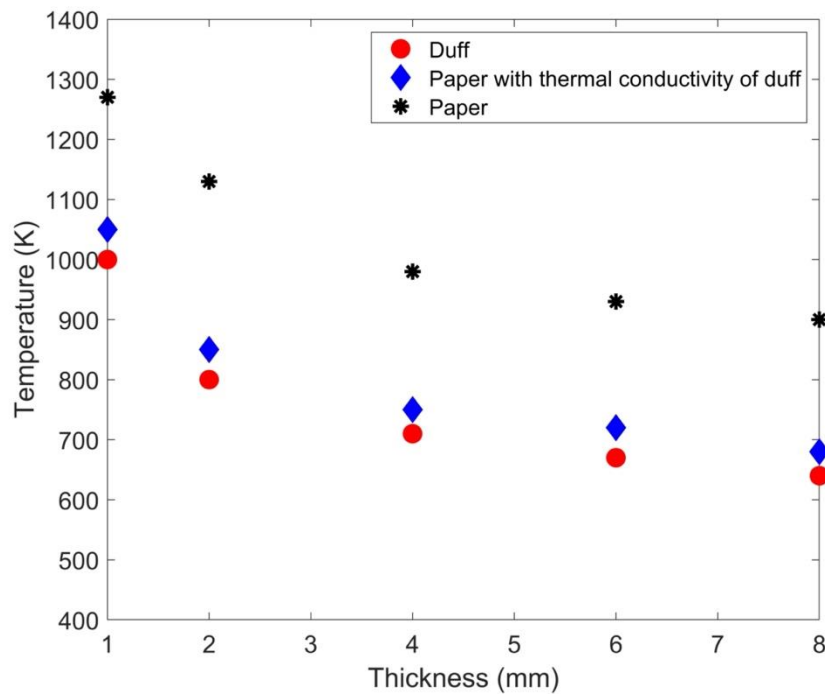


Figure 5.5.5. Ignition temperature with varying metal layer thickness, comparing paper, modified paper (with the thermal conductivity of duff), and duff.

We also examined the effect of the type of metal, by repeating the simulations for steel 302/304. In practical scenarios the hot metal particles that drop onto forest beds can be of different materials. Figure 5.2.6 shows the ignition temperatures for aluminum and steel for the eight fuel types, with varying metal layer thickness. These simulations used temperature increments of 5 K to capture small variations in the response. At smaller metal thicknesses (i.e., 1 mm), nearly all fuels exhibit a lower ignition temperature for aluminum, 40–60 K below that for steel—with the exception of peat, where the trends from the two metals match closely. Urban et al. [12] found similar results in their experimental studies: grass fuel beds ignite at lower ignition temperatures with hot aluminum particles. There can be two reasons for aluminum to cause lower ignition temperatures: higher thermal conductivity and latent heat added during melting. The behavior of peat suggests that the latent heat has a higher impact, since the ignition temperatures from aluminum and steel match closely. The ignition temperatures of peat are lower than the melting temperature of aluminum, so latent heat has no impact on its behavior. Smoldering temperatures in the other fuels exceed the melting point of aluminum, and so the properties of molten aluminum play a role in those cases. For larger particle sizes, the differences between the metals decrease, as heat losses to the environment increase, and the impact of metal material drops.

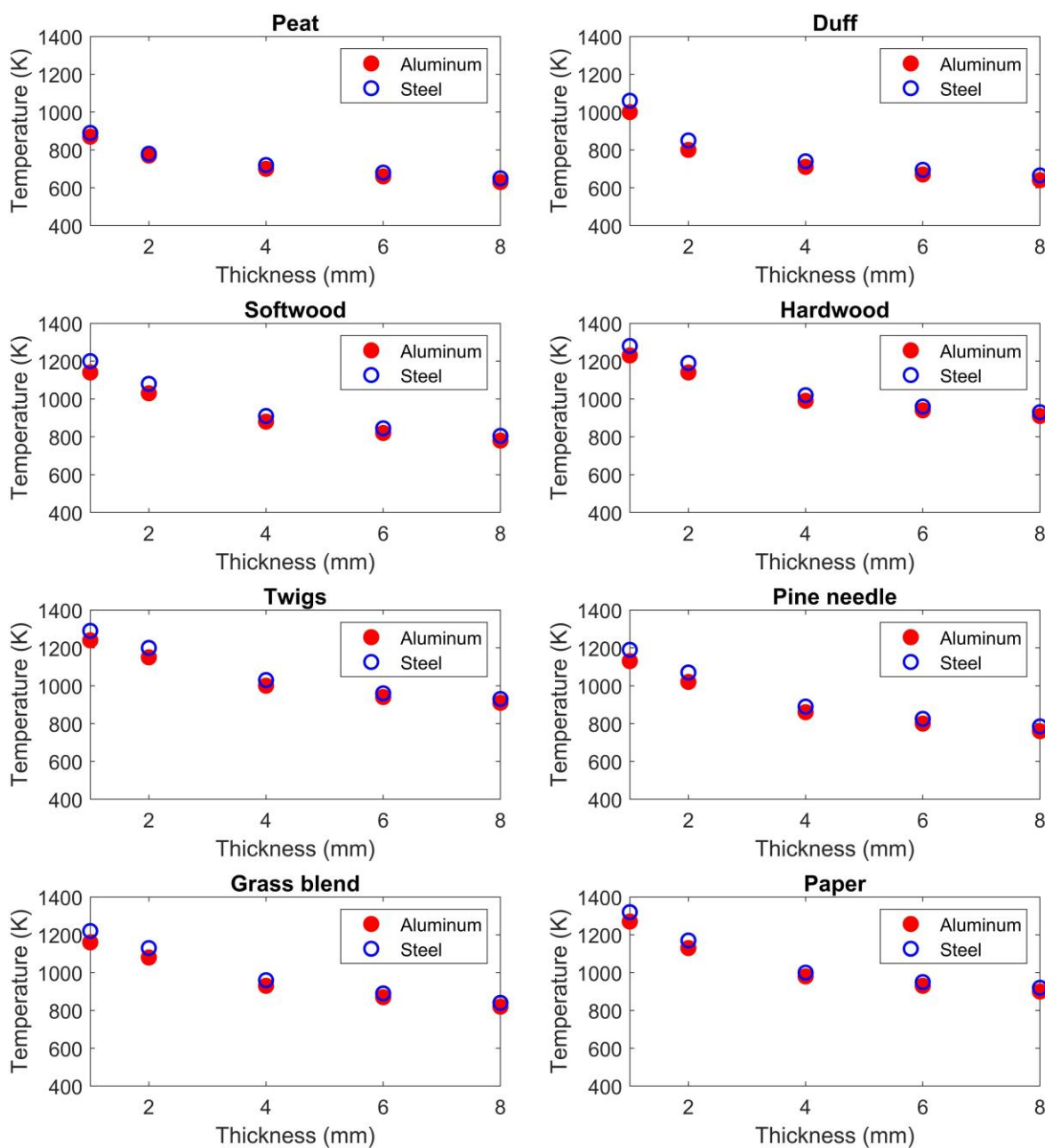


Figure 5.5.6. The ignition temperatures for aluminum and steel for the eight fuel types, with varying metal layer thickness.

5.6 Emissions from Smoldering Samples

Emission measurements focused on laboratory studies with coincident IR camera measurements which provided physical data on the duff combustion process —surface temperature and rate of spread— which could link emissions to physical-models of smoldering combustion. The laboratory emission measurements were obtained over burns of 10 duff samples conducted in January 2020 and May 2021 at the Oregon State University testing facility. During the laboratory burns, 80 emission samples were collected. Most of the emission samples measured carbonaceous gases (CO_2 , CO , CH_4 , and 20 NMHC) and total $\text{PM}_{2.5}$, but a subset of samples measured organic carbon (OC) and elemental carbon (EC, i.e. black carbon) content of $\text{PM}_{2.5}$. The laboratory burns are summarized in Table 5.6.1. The emission measurements were used to quantify emissions factors (EF, g kg^{-1}), emission rates (ER, mg s^{-1}), and emission fluxes (EM, $\mu\text{g m}^{-2} \text{s}^{-1}$) (see Section 4.5) for the 22 measured gases and $\text{PM}_{2.5}$.

This section is organized into four subsections. In section 5.6.1 we summarize the pollutant EF, and EM measured in the laboratory studies. The laboratory results are compared with those obtained in a set of limited field measurements of emissions from prescribed fires in section 5.6.2. Section 5.6.3 evaluates the emission measurements in the context of smoldering behavior. Finally, the discussion of section 5.6.4 compares our laboratory and field findings with previously published results from emission studies of smoldering duff and peat soils.

Table 5.6.1. Summary of laboratory duff burns.

Burn	Date	Duff moisture content (%)	Duff packing density (kg m^{-3})	Duff depth (cm)	Number of emission samples		
					Gas	$\text{PM}_{2.5}$	OC/EC
1	1/28/2020	19.7			7	7	2
2	1/29/2020	17.0			9	8	4
3	1/30/2020	5.8			6	0	1
4	1/31/2020	13.1			15	15	2
5	5/12/2021	13.2	44.8	3.18	7	7	0
6	5/12/2021	40.8	74.4	3.81	14	14	0
7	5/13/2021	7.0	71.4	4.57	11	10	1
8	5/13/2021	9.3	128.1	3.02	13	11	2

5.6.1. Summary of Laboratory Emission Measurements

Emission factors for CO_2 , CO , CH_4 , and $\text{PM}_{2.5}$, MCE and CE that were measured in eight laboratory burns are summarized in Table 5.6.2. Inefficiency of the combustion process, and hence total pollutant production, is best summarized with CE, the fraction of volatilized carbon released as CO_2 . The study found that average CE across 80 emission samples was 75% with a range of 47% to 88%. EF for $\text{PM}_{2.5}$, the primary pollutant of concern from smoldering, varied considerably with a coefficient of variation of 98% around the study mean of 37.3 g kg^{-1} . Emission factors for NMHC are presented graphically in Figure 5.6.1. Of the measured NMHC, emissions are greatest for the C2 species (ethane, ethene, and ethyne).

Burn average CE and EF for CH_4 , NMHC and $\text{PM}_{2.5}$ for the six duff samples for which emission data has been analyzed are shown in Figure 5.6.1. The variability in CE and EF fluctuates

considerably across the burns, with variability being least for burn 4 for CE and all three EF. For CE and EFPM_{2.5} burn 2 has the greatest variability, while burn 7 has the greatest variability for EFCH₄ and EFNHMC. There is no obvious relationship between CE and EF variability and duff moisture content (Figure 5.6.1 and Table 5.6.1).

Table 5.6.2. Laboratory study aggregate statistics for emission factors (EF) for CO₂, CO, CH₄, and PM_{2.5} (g kg⁻¹), combustion efficiency (CE), and modified combustion efficiency (MCE).

Variable	N	Mean	Median	SD	Min.	Max.
EFCO ₂	80	1361	1378	132	861	1618
EFCO	80	201	208	35	120	271
EFCH ₄	80	5.91	4.55	2.40	1.70	14.60
EFPM _{2.5}	71	37.6	25.9	36.7	5.0	202.4
CE	80	0.74	0.75	0.07	0.47	0.88
MCE	80	0.81	0.81	0.03	0.75	0.90

The EF of many pollutants are correlated with MCE. EF for CH₄, NMHC, PM_{2.5} and a wide range of oxygenated organic gases have been found to increase with decreasing MCE for many fuel types and linear functions of MCE have been widely used to predict EF and inventories of pollutant emissions. However, the limited studies of exclusively smoldering fuels published to date have tended to show little or no correlation between MCE and EF. Likewise, our study found no correlation between MCE and EF for CH₄, NMHC, PM_{2.5} (Figure 5.6.2). Interestingly, we did observe a robust correlation between CE and EFPM_{2.5} (lower right panel of Figure 5.6.3), but much less so for EFCH₄ ($r = -0.28$, $p = 0.011$) and EFNHMC ($r = -0.38$, $p = 6.6e-4$).

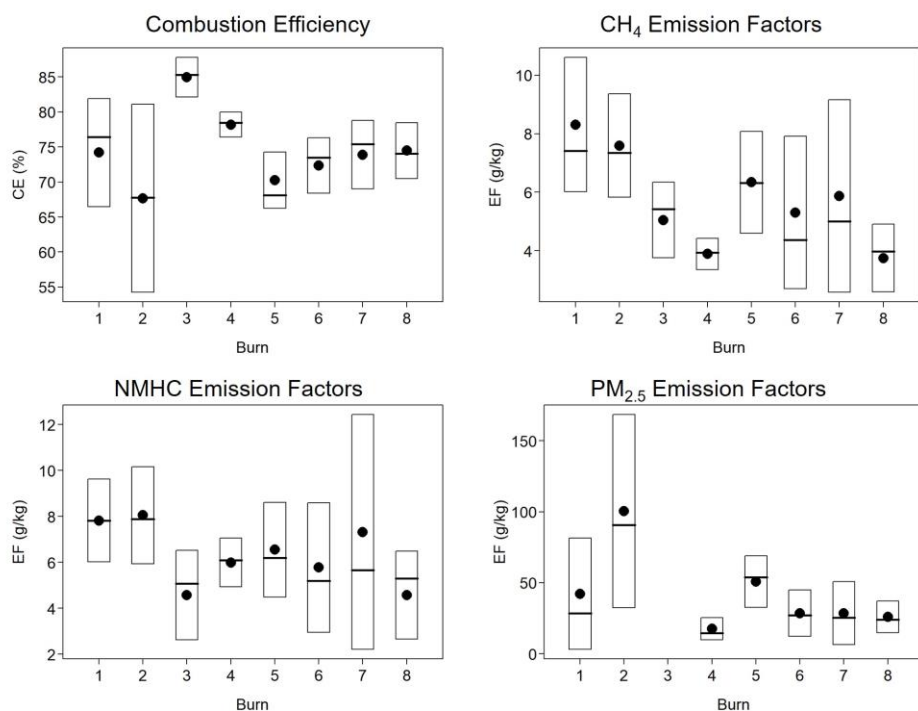


Figure 5.6.1. Laboratory study combustion efficiency (%) and CH₄, NMHC, and PM_{2.5} emission factors (g kg⁻¹) by burn. Circles and horizontal lines are mean and median values and boxes are ± 1 standard deviation.

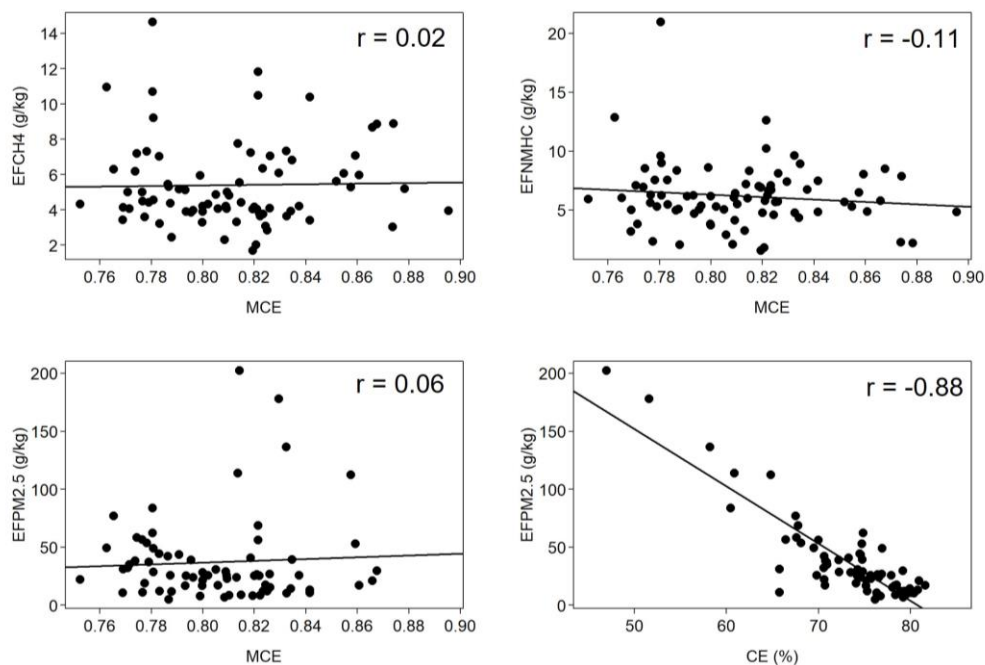


Figure 5.6.2. Laboratory study EF for CH₄, NMHC, and PM_{2.5} plotted versus MCE and PM_{2.5} EF versus CE. The p-values associated with the correlation coefficients (Pearson's product-moment correlation) are $p = 0.85$, $p = 0.31$, $p = 0.64$, $p < 2.2e-16$ for CH₄, NMHC, and PM_{2.5} vs MCE and PM_{2.5} versus CE, respectively.

5.6.2. Comparison of Laboratory Results with Field Data

EF from the field study and laboratory burns are compared in Table 5.6.3. MCE values for the flame front prescribed fires were 0.86 and 0.87, somewhat higher than for the point source and lab burns, and at the upper end of the range for smoldering. The other MCE values were in a typical range for smoldering. The CO₂ emission factors for the flame front fires were correspondingly the highest. The CO emission factors were in a range that could be expected for smoldering combustion, ranging from 149 g/kg for Goat #6 field to 220 g/kg for Lab burns 2021. The methane emission factors for both the field and lab experiments were similar, in a range of 4.5 to 6.6 g/kg. There were differences in some of the hydrocarbon species – some were higher in the field results and others in the lab burns, although most were at low values (< .30 g/kg) making it difficult to draw any conclusions based on fuel chemistry, or combustion efficiency.

Table 5.6.3. MCE and emission factors (g/kg) for the two prescribed fires, an average point source burn results, and averaged values for the 2020 and 2021 lab burns.

	Winthrop 1 Flame front	Goat #6 Flame front	Winthrop 2 Point Sources	2020 Lab Average	2021 Lab Average
MCE	0.860	0.870	0.810	0.836	0.798
CO	165	149	215	172	218
CO ₂	1546	1572	1459	1393	1360
CH ₄	5.6	4.9	6.6	5.9	4.8
C ₂ H ₆	0.88	1.17	1.45	1.46	1.11
C ₂ H ₄	1.16	0.86	1.25	1.29	1.00
C ₂ H ₂	0.05	0.00	0.02	0.73	0.25
C ₃ H ₈	0.50	0.40	0.69	1.24	0.80
C ₃ H ₆	0.89	0.78	1.11	0.08	0.77
C ₃ H ₄	0.00	0.00	0.00	0.26	0.15
isobutane	0.03	0.09	0.07	0.00	0.07
Butane	0.14	0.18	0.24	0.05	0.20
t-2 butene	0.09	0.08	0.09	0.14	0.21
Butene	0.18	0.16	0.23	0.26	0.36
isobutene	0.20	0.21	0.28	0.38	0.19
c-2-butene	0.07	0.05	0.07	0.10	0.06
1,3- butadiene	0.04	0.03	0.08	0.14	0.10
isopentane	0.02	0.04	0.03	0.10	0.11
Pentane	0.07	0.09	0.13	0.09	0.08
c-2 pentene	0.03	0.04	0.03	0.05	0.10
1-pentene	0.10	0.08	0.12	0.13	0.09
t-2- pentene	0.02	0.01	0.02	0.11	0.06
Hexane	0.01	0.00	0.08	0.05	0.10

Figure 5.6.3 compares carbon release rates of the field and laboratory burn. The rate of carbon release was comparable for the field and lab burns, in a range of .1 to 5 g C/m²/ min. Values

lowest for the flame front samples, less than 1 g C/m²/ min., except for the first Rendezvous sample. The point source rates were significantly higher, 2 to 5 g C/m²/ min. for #1 and 1 to 3.5 for #2. The 2020 lab burns were in a range of .15 to 2, and up to 4.5 g C/m²/ min. for the 2021 lab burns. The lower values for the flame front resulted from the ignition method – natural conditions of the fire burning through the plot vs. manual, controlled ignition. Some of the carbon release rates for field and lab burns displayed a curved pattern of rising then decreasing, including Goat #6, Point Source 2, and Lab Burns 7 and 8, whereas the first flame front burn, Rendezvous, peaked with the first sample, exponentially decreasing subsequently.

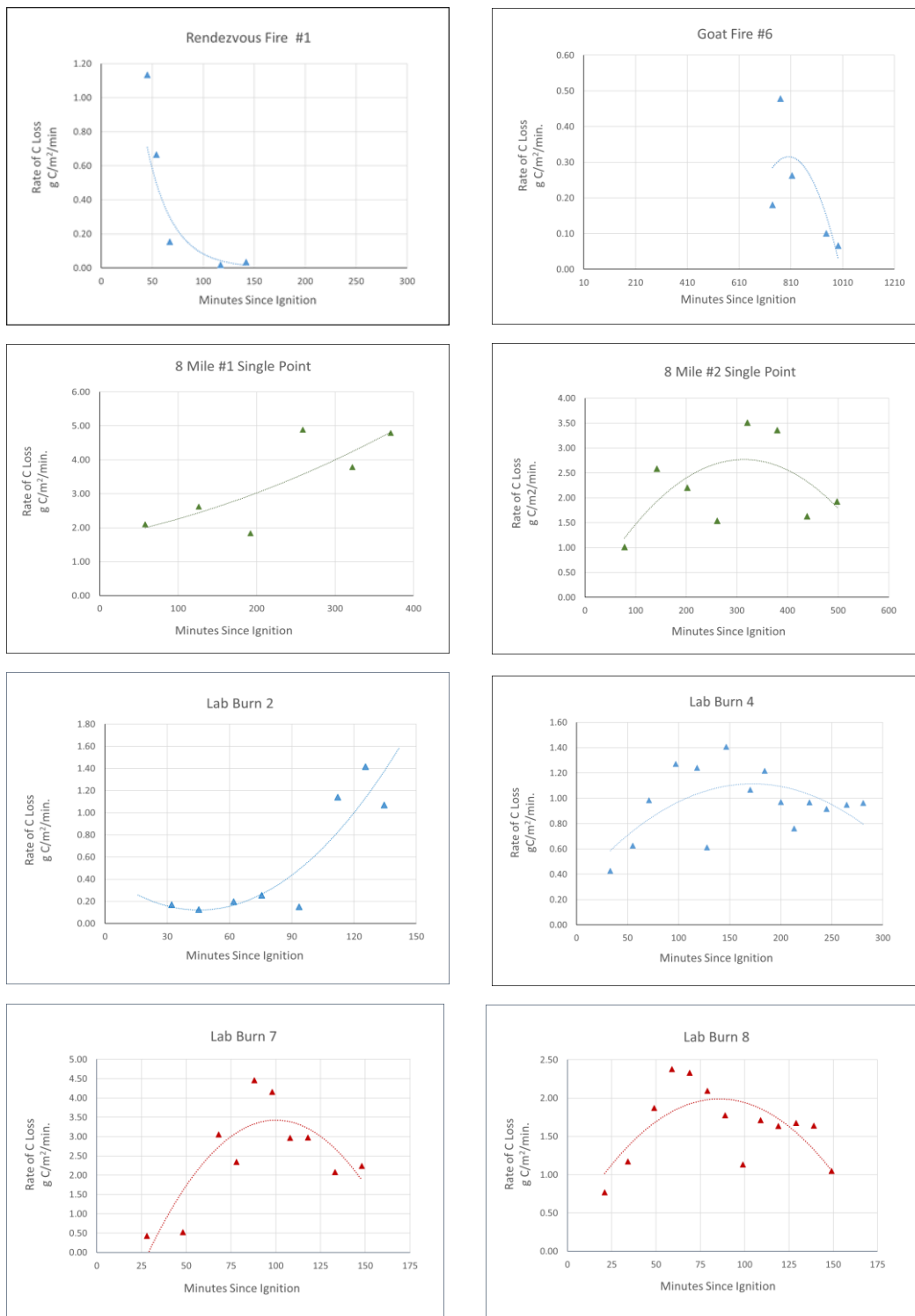


Figure 5.6.3. Comparison of rate of carbon release for field studies (prescribed fire and point source). and laboratory burns in 2020 and 2021.

5.6.3 Emission Factors and Combustion Efficiency

An important objective of this project is to determine how EF (i.e., smoke composition) and pollutant emission rates vary with smoldering behavior, in particular the spread rate of the smoldering front and surface temperature. We begin discussing EF with respect to spread rate. In Figure 5.6.4 CE and EF for CH₄, NMHC, and PM_{2.5} are plotted versus the smoldering front rate of spread. We were unable to derive spread rates for burn 1 due to accidental, frequent obstruction of the camera with the emissions sampling apparatus. These errors in the sampling approach were corrected for the subsequent burn. The project data evaluated to date indicates that as the spread rate increases the yield of CO₂ (CE) decreases and EF for CH₄, NMHC, and PM_{2.5} increase (Figure 5.6.4). However, a simple linear regression model may explain only a small portion of EF variability ($R^2 = 0.21, 0.18,$ and 0.30 for EFCH₄, EFNHMC, and EFPM_{2.5}, respectively). Correlation and linear regression statistics for all EF are provided in Appendix Table A.1.

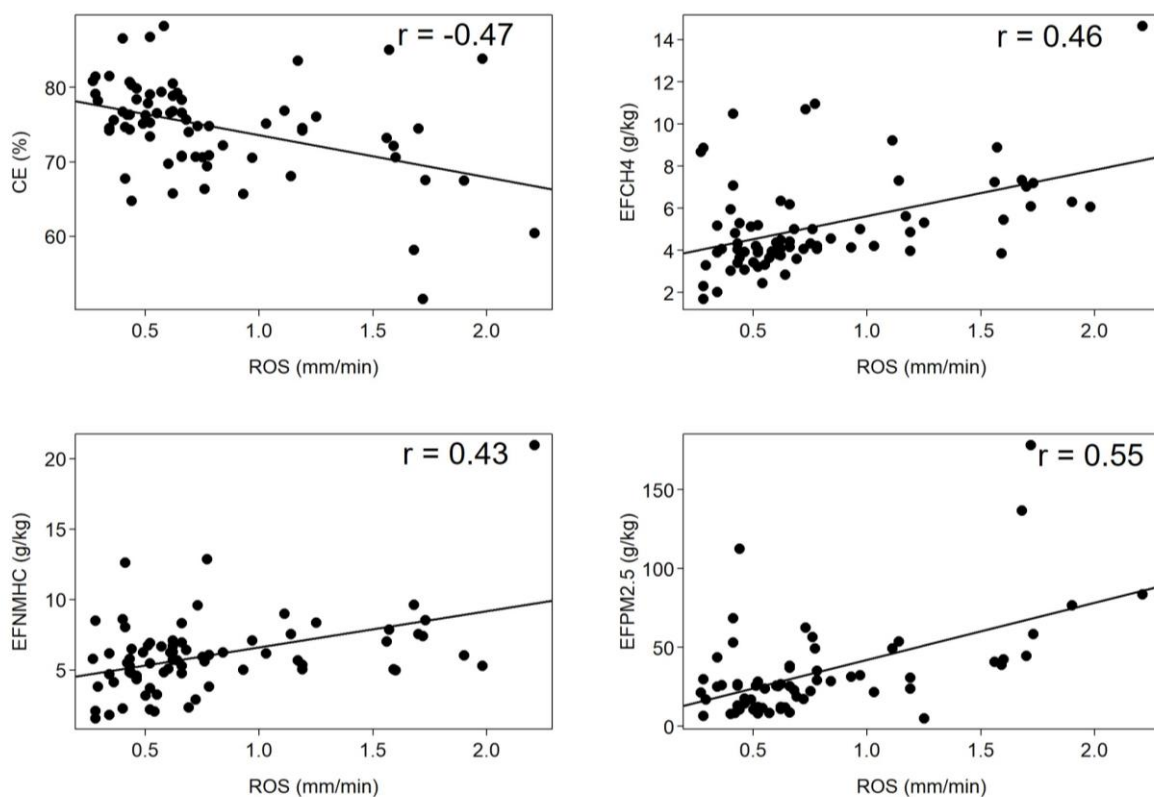


Figure 5.6.4. Laboratory study CE and emission factors for CH₄, NMHC, and PM_{2.5} plotted versus smolder front rate of spread. The p-values associated with the correlation coefficients (Pearson's product-moment correlation) are $p < 3e-4$, $p < 5e-5$, $p < 2e-4$, $p < 4e-6$ for CE, EFCH₄, EFNHMC, and EFPM_{2.5}, respectively.

The relationship between the average surface temperature of the smoldering duff, T_{sfc} , and EF for CH₄, NMHC, and PM_{2.5} and CE is explored in Figure 5.6.5. As with the spread rate, we find EFCH₄, EFNHMC, and EFPM_{2.5} are positively correlated with T_{sfc} , while CE exhibits no significant correlation. As T_{sfc} increases from 250 C to 300 C, EFCH₄ and EFNHMC both increase ~ 50%, while EFPM_{2.5} shows a much greater increase, more than doubling in value. In comparison with EFCH₄ and EFNHMC, a marked increase in variability for $T_{sfc} > 270$ C is

observed. Below 270 C, the coefficient of variation (CV) is similar for EFCH₄, EFNHMC, and EFPM_{2.5} at 37%, 37%, and 58%, respectively. However, for T_{sfc} > 270 C, the CV for EFPM_{2.5} increases to 81%, while that for EFCH₄ (CV = 38%) and EFNHMC (CV=45%) increase only slightly. As with spread rate, a simple linear regression model with T_{sfc} as the independent variable may explain only a small portion of EF variability (R² = 0.28, 0.12, and 0.32 for EFCH₄, EFNHMC, and EFPM_{2.5}, respectively) and the behavior of EFPM_{2.5} suggests a non-linear relationship with T_{sfc}. Correlation and linear regression statistics for all EF are provided in Appendix Table A.1.

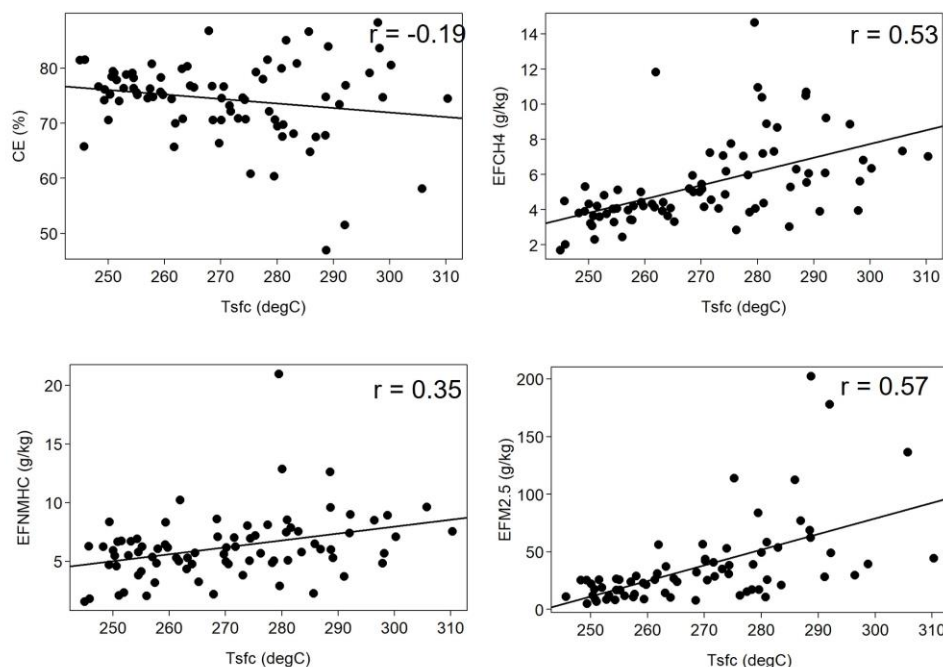


Figure 5.6.5. Laboratory study CE and emission factors for CH₄, NMHC, and PM_{2.5} plotted versus surface temperature (deg) (see text for details). The p-values associated with the correlation coefficients (Pearson's product-moment correlation) are: p = 0.10, p = 4.0e-7, p = 0.002, p = 2.6e-7 for CE, EFCH₄, EFNHMC, and EFPM_{2.5}, respectively.

Predicting smoke impacts on air quality requires pollutant fluxes (mass/area/time) as input for smoke dispersion and air chemistry models. In air quality and climate modeling the flux of pollutant X (EMX) from biomass burning is commonly calculated as the product of EFX and fuel load consumption rate (kg m⁻² s⁻¹). This approach assumes that EFX is independent of the fuel load consumption rate. However, the correlation we have observed between EF (EFCH₄, EFNHMC, and EFPM_{2.5}) and spread rate and T_{sfc} indicate that this may not be the case for smoldering duff. One project objective is to link emission fluxes to combustion characteristics, such as spread rate and T_{sfc}, to predict emissions directly from physics-based models of smoldering combustion. Figure 5.6.6 plots EM of total C, C_{tot}, CH₄, NMHC, and PM_{2.5} versus rate, where EM were calculated using the area of active smoldering (T_{sfc} > 220 C) within the footprint of the emissions sampling chamber. EMCH₄ and EMNMHC are positively correlated with rate of spread, while EMC_{tot} and EFPM_{2.5} have no significant correlation. When EM for

C_{tot} , CH_4 , NMHC, and $\text{PM}_{2.5}$ are compared with $T_{\text{sf}}c$ we find no significant correlation as shown Figure 5.6.7.

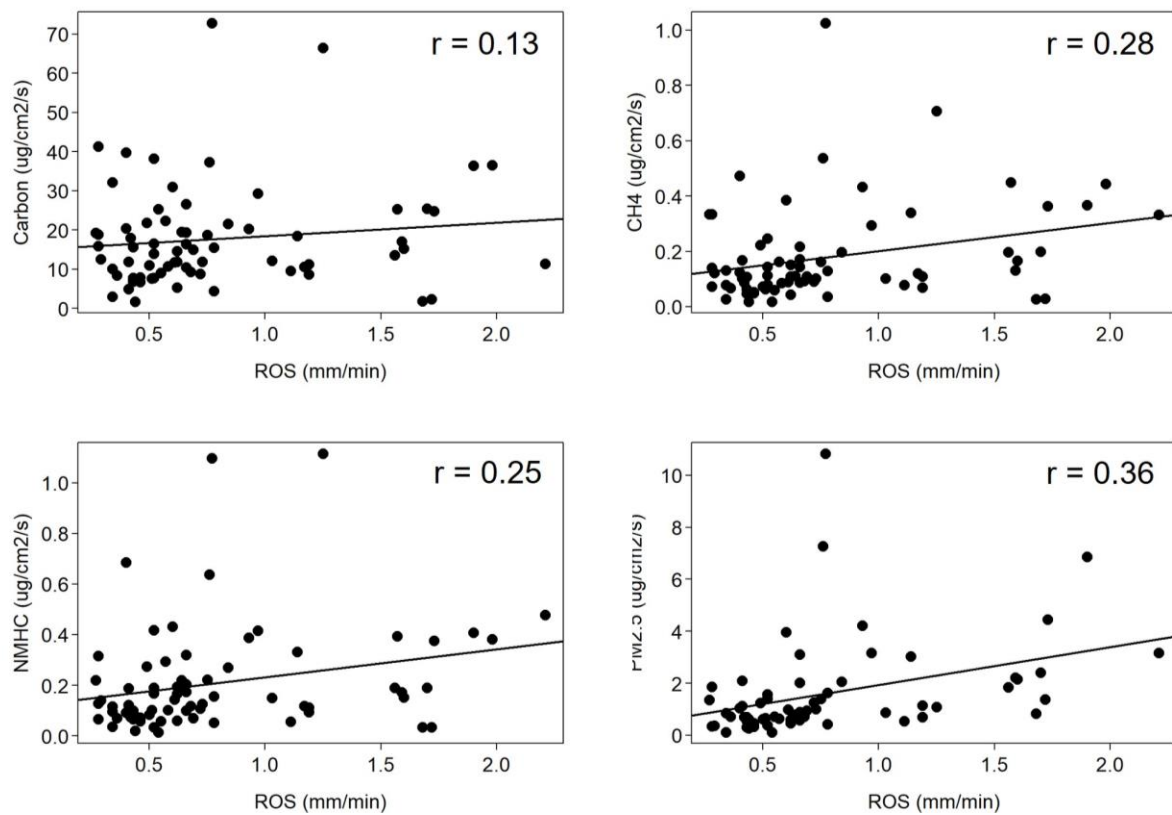


Figure 5.6.6. Laboratory study emission fluxes ($\mu\text{g}/\text{cm}^2/\text{s}$) of total carbon, CH_4 , NMHC, and $\text{PM}_{2.5}$ plotted versus rate of spread (mm/min) (see text for details). The p-values associated with the correlation coefficients (Pearson's product-moment correlation) are $p = 0.29$, $p = 0.016$, $p = 0.03$, $p = 0.003$ for total carbon, CH_4 , NMHC, and $\text{PM}_{2.5}$, respectively.

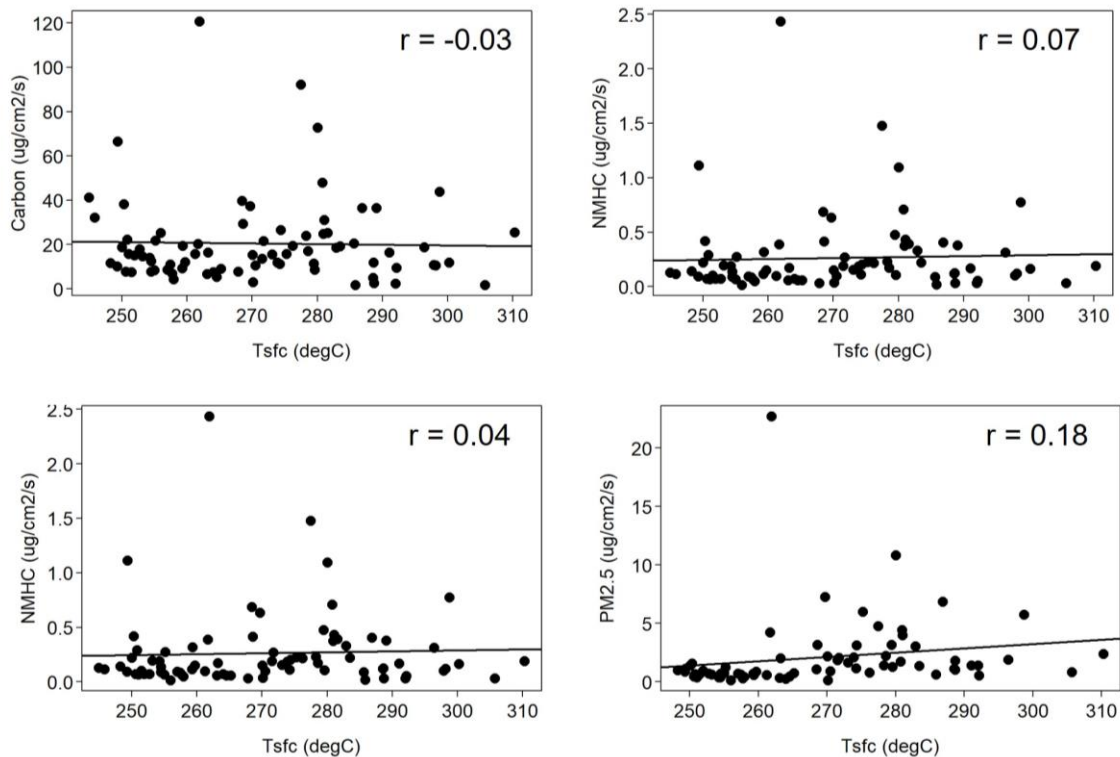


Figure 5.6.7. Laboratory study emission fluxes ($\mu\text{g}/\text{cm}^2/\text{s}$) of total carbon, CH_4 , NMHC, and $\text{PM}_{2.5}$ plotted versus surface temperature. The p-values associated with the correlation coefficients (Pearson's product-moment correlation) are $p = 0.83$, $p = 0.53$, $p = 0.74$, $p = 0.14$ for total carbon, CH_4 , NMHC, and $\text{PM}_{2.5}$, respectively.

5.6.4 Comparison with Previous Studies

There are numerous studies that have measured the emissions of smoldering peat in a laboratory setting. Watson et al. [98] utilized a lab setup that induced smoldering using an induction heater beneath the duff sample. Peat samples from three locations in Russia and Alaska were burned. The resulting MCE values of this work were 0.85, 0.81, and 0.85, very similar to those that we obtained from our field and lab studies (Table 5.6.4). Hu et al. [13] burned sphagnum peat moss in a lab and measured the emissions by FTIR. During what was defined as the steady state phase of smoldering the measured emission factors of C_2H_2 , C_2H_4 , and C_3H_6 were 0.17, 6.6, and 0.05 g/kg respectively. The values for these EFs from our lab study were 0.10, 0.93, and 0.94 g/kg, from Douglas fir forest duff, so the difference in fuels may be important. The average EF for $\text{PM}_{2.5}$ [13] was 23.1 g/kg, lower than our value of 37.3 from the lab studies. Our MCE values, 0.75 – 0.90, largely fell within the range of published values for peat smoldering, both field and lab. The same was true for CO_2 , CO, and CH_4 emission factors – the range from this study was within the range of published values (Table 5.6.4).

Table 5.6.4. Published MCE values and emission factors (g/kg) for smoldering peat emissions from laboratory and field studies.							
	Study	Peat type	Location	MCE	EF CO ₂	EF CO	EF CH ₄
Watson et al. (2019)	Lab	boreal	Pskov, Siberia	.85	1380	159	6.9
Watson et al. (2019)	Lab	boreal	Odintsovo, Russia	.81	1073	157	3.2
Watson et al. (2019)	Lab	boreal	Northern Alaska	.85	1400	161	5.7
Chakrabarty et al. (2016)	Lab	boreal	Northern Alaska	-	1598	128	-
Yokelson et al. (1997)	Lab	temperate	Minnesota, Alaska	.81	1395	209	6.9
Stockwell et al. (2014)	Lab	temperate	Ontario	.80	1274	197	6.2
Smith et al. (2018)	Field	tropical	Malaysia	.80	1580	251	11
Stockwell et al. (2016)	Field	tropical	Indonesia	.77	1564	291	9.5
Geron and Hays (2013)	Field	temperate	Pocosin Lakes NWR, NC USA	.77 - .83	1100 - 1640	10 -280	-
This study - flame front	Field	temperate	Winthrop, Washington	.86	1559	157	5.3
This study - point source	Field	temperate	Winthrop, Washington	.81	1459	215	6.6
This study	Lab	temperate	Oregon DF	.81	1361	201	5.4

6. Conclusions and Implications

In summary, this project focused on systematically evaluating how the chemical composition (e.g., lignin content) and physical characteristics of the fuel bed (e.g., particle size, moisture content) collectively influence smoldering behavior. Historically, most studies related to smoldering have focused on understanding the smoldering behavior of specific fuels and conditions. A limitation of this approach is that it can be challenging to understand how to apply the knowledge to new conditions (e.g., different densities) or new fuels. However, by systematically considering individual factors that influence smoldering behavior it is expected that smoldering behavior could be predicted, within reasonable accuracy, even for fuels that have not been evaluated. To this end, surrogate fuels composed of hemicellulose, cellulose, and lignin were burned and compared to natural fuels with similar compositions. The results suggest that surrogate fuels can be used to mimic the burning behavior of natural fuels to a reasonable degree of accuracy, depending on the fuel. Additional evaluation of the use of surrogate fuels is required.

Corresponding experiments and analysis were performed to identify smoldering behavior of real fuels, specifically duff samples collected underneath Douglas-fir and ponderosa pine trees. These two fuels are native and significant to much of the Western United States of America. Note that the duff samples were collected in regions that are more arid (i.e., ponderosa pine) or moister (i.e., Douglas-fir) and have relatively different thicknesses and compositions. The smoldering results from burning duff samples are expected to be applicable to a variety of natural fuels as a result of burning samples that have quite different properties. The results from these studies help to bridge the results from the well-controlled laboratory and numerical studies to realistic fuels.

Data of particulate and gaseous emissions were collected from the duff samples and correlated to the burning behavior. Measurements of emission characteristics and fluxes are important for ultimately better predicting environmental impacts of smoldering burns.

Specific conclusions from this work are listed below followed by a discussion of the implications of the research and recommended future work.

6.1 Influence of Chemical Composition of Fuels on Smoldering Behavior

6.1.1 Influence of Cellulose and Hemicellulose Content

1. When density is fixed, propagation velocities tend to increase with increasing hemicellulose content. This is caused by the earlier pyrolysis and higher temperatures that occur when hemicellulose is present in the fuel. When the fuel is loosely packed and the density is not controlled, horizontal propagation velocities increase with cellulose. This is due to the lower densities naturally occurring with higher cellulose contents.
2. For downward propagation, the greatest change in smoldering speed occurs when decreasing the cellulose content from 100% to 85%, but there is relatively little change between 85% and 50% cellulose. This behavior illustrates a non-linear behavior of downward smoldering propagation speeds to the composition of the fuel.

6.1.2 Influence of Lignin Content

3. Fuels with higher lignin content smolder at slower horizontal and vertical propagation speeds. This behavior is caused by slower pyrolysis and higher activation energy of lignin.

4. As the lignin content increases, the impact of the relative amount of hemicellulose and cellulose decreases. Once the fuel is composed of 20-30% lignin, lignin is the dominant chemical component in influencing smoldering propagation behavior due to its slower reaction rates.
5. Once a minimum concentration of hemicellulose is present in the fuel additional hemicellulose does not increase the propagation velocity for mixtures of lignin, hemicellulose, and cellulose. This observation is consistent with trends for binary mixtures of cellulose and hemicellulose. The earlier pyrolysis and oxidation in hemicellulose helps spur the reactions, but there are diminishing returns with sufficient concentration of lignin.
6. In contrast, both lignin and hemicellulose contents are correlated with the peak temperature of smoldering. This sensitivity is attributed to the formation of ash that reduces the radiation loss across pores in the fuel.
7. The minimum radiant heat flux and exposure time required for smoldering ignition depends on fuel composition and can vary by 25% (from 7–8.8 kW/m²). This variation comes from the activation energy of the fuel oxidation reactions, which is lower for cellulose than lignin and hemicellulose.
8. For ignition due to conduction from a hot metal particle, the ignition temperature also depends on fuel composition, and can vary over 300 K depending on the thickness of the metal. This dependence comes from the varying thermal conductivity of the fuels.
9. Peak temperatures decrease with lignin experimentally. The heat losses associated with the longer time required for lignin to burn counteract the potential higher temperatures observed computationally from higher char yield and heat of combustion of lignin. This observation underscores the importance of correctly modeling heat losses from models.
10. Fuels with lignin derived from pine had faster propagation velocities because of earlier pyrolysis and oxidation compared to lignin derived from tobacco. This indicates that the source of the lignin for experiments can have an impact on smoldering behavior and may need to be considered when considering the lignin in different natural fuels.

6.2 The Efficacy of using Surrogate Fuels

11. Burning of surrogate fuels composed of lignin, hemicellulose, and cellulose can reasonably match the horizontal propagation velocities of ground Douglas-fir and wheat straw. However, downward propagation velocities are only similar when the inorganic content is minimal. Greater inorganic contents in the natural and surrogate fuels causes greater differences in smoldering propagation rates. The differences in downward smoldering in the higher inorganic content cases may be due to differences in ash layer development.

6.3 Influence of Density and Moisture Content

12. The expansion of fuels caused by moisture content causes the propagation speed of smoldering to increase, due to the reduction in density. If the fuel does not expand with the addition of water (i.e., water fills the fuel pores), the propagation speeds *drop* primarily due to increase in wet bulk density. In both cases, additional moisture content reduces the mean peak temperature slightly.
13. The critical moisture content of ignition and extinction is mostly insensitive to fuel composition, except for fuels with higher amounts of hemicellulose, where the increased heat release and elevated peak temperature allow sustained smoldering even at higher

moisture content. Thus, fuels with high hemicellulose contents can ignite—and remain smoldering—at higher levels of moisture content.

14. For mixtures of cellulose and hemicellulose, horizontal and downward propagation velocities decrease with density. Fuels with hemicellulose have less of a change in horizontal spread with density than pure cellulose. These trends with density are attributed to the larger amount of fuel to burn and changes in oxygen diffusion.
15. Adhesion of the fuel and subsequent cracks that can form while burning can cause a notable impact (i.e., reduction) on horizontal smoldering spread. The reduction in propagation rates occurs because the dominant mode of heat transfer becomes radiation heat transfer at the crack interface, whereas both conduction and radiation facilitate heat transfer for continuous fuels. It is expected that models will over predict smoldering propagation rates if the physics of cracks in the fuel beds are not captured.
16. The experimental results indicate that reductions in horizontal propagation rates because of increasing moisture content are caused, in part, because of cracks in the fuel that form. This is suggested by a greater reduction in horizontal propagation rates than downward propagation rates as the moisture content is increased. Cracks can form in the fuel (due to adhesion of the fuel) while smoldering burns spread horizontally, but no such cracks are observed for downward smoldering burns.

6.4 Influence of Particle Size on Smoldering Behavior

17. Smaller particles are more prone to self-sustained smoldering and have higher surface and downward smoldering spread rates in porous beds with homogenous particle sizes. Limits in self-sustained smoldering based on particles being sufficiently small are not evident, at least within the ranges evaluated in this study (i.e., $d > 0.5$ mm). The sensitivity of smoldering behavior to particle size is independent of the ignition temperature or heating rate.
18. For fuel beds with mixed particle sizes, relatively larger particles can smolder along the surface if smaller particles are present in the voids. Such physical characteristics are expected for duff. Increasing the particle size requires a larger percentage (by mass) of smaller diameter particles to sustain self-sustained smoldering. Smaller particles facilitate heat being transferred from the reaction zone to virgin fuel.

6.5 Effect of Wind on Smoldering Behavior

19. Smoldering spread rate increases with wind speed. The spread rate at 1 m/s is double the spread rate seen in the same fuel under windless conditions. The increase is attributed to increased oxygen availability.
20. Smoldering temperatures increase with wind speed.
21. The smoldering front under wind conditions appeared to progress in 3 stages. First, fuel ahead of the smoldering front began to crack due to fuel shrinkage creating a gap in the fuel. Second, the smoldering front progressed over and/or around the crack until the smoldering front encompassed the crack in the fuel. Third, once the smoldering front is over the cracked portion of the fuel the smoldering front progressed downward until reaching the bottom of the reactor box. The smoldering front does not progress horizontally during the third stage and is only able to progress horizontally through the repetition of the process, starting with a new crack in the fuel.

6.6 Emissions from Smoldering Burns

22. Physical properties of duff and peat soils, in particular moisture content, packing density, and mineral content, have been identified as important factors affecting the ignition and propagation of smoldering combustion. A primary objective of this project's emissions component was to determine which chemical and physical properties of fuels limit/control emissions of smoldering combustion. A total of eight laboratory burns were conducted. Unfortunately, the eight burns were insufficient to isolate the role of duff properties (moisture content, packing density) on emissions from that of the smoldering behavior (surface temperature and spread rate) due to the high natural variability in duff samples and emissions.
23. A key project objective was to develop relationships between emissions, EF and EM, and smoldering behavior. The project focused on smoldering front spread rate and surface temperature as possible drivers of emissions. We found that EF for CH₄, NMHC, and PM_{2.5} increased with increasing surface temperature and spread rate. However, with respect to EM, the only significant relationship observed was a muted positive correlation of EMCH₄ and EMNMHC with spread rate. We are currently pursuing a multivariate analysis, including spread rate, surface temperature, and duff physical properties, to develop predictive smoldering emission models.

6.7 Implications of Research

Five implications of the research are highlighted in this section. Interested readers are referred to the list of publications in the Appendix as well as subsequent publications that will result over the next 2 years for additional information.

The first major implication from our work is evidence that fire managers may be overestimating $\text{PM}_{2.5}$ emissions and, as a result, unnecessarily limiting much needed use of prescribed fire. Laboratory burns were used to measure EF for CO_2 , CO, CH_4 , $\text{PM}_{2.5}$ and 22 NMHC for Douglas fir forest duff, a smoldering prone ground fuel that is representative of conifer forest ecosystems across much of the western US. Douglas-fir duff serves as a reasonable proxy for duff found in many forest types present at DoD facilities, although it is noted that the fuel loading will vary for different species. The laboratory findings were found consistent with a limited set of field measurements from prescribed burns indicating the lab results may be applied to fires in the natural environment. Currently, the EF used for smoldering duff and peat in two widely used smoke production models, FOFEM and CONSUME, are MCE-based extrapolations of EF measured for non-duff/peat fuels. For example, FOFEM uses $\text{EFPM}_{2.5} = 40 \text{ g kg}^{-1}$ for smoldering western conifer duff [99]. Our study finds the true value of $\text{EFPM}_{2.5}$ is closer to 26 g/kg^{-1} , indicating fire managers may have been overestimating $\text{PM}_{2.5}$ emissions and unnecessarily limiting much needed use of prescribed fire. The emission factors quantified in this study will enable more accurate prediction of pollutant emissions from smoldering duff in prescribed fires on DoD lands and fires in western conifer forests.

The second implication of this study is that a new methodology and conceptual framework for considering smoldering behavior of natural fuels has been established and this shift has the potential to be transformative. Historically, the majority of smoldering studies have tended to focus on obtaining and analyzing the results for smoldering burns for a specific fuel (e.g., peat) for a specific range of bed conditions (e.g., moisture content or density). Hence, the results and understanding tend to be very specific. This can be problematic when seeking to understand how to apply knowledge from studies to new fuels or new conditions (e.g., different ranges of moisture content, packing densities). The situation is further complicated when recognizing that hundreds, if not thousands of different fuels and fuel conditions are considered and yet an ability to predict smoldering behavior is needed. In this work the fuels were considered as their fundamental constituents (i.e., cellulose, hemicellulose, and lignin) and physical characteristics (e.g., density, particle sizes). This approach has allowed new insights into smoldering behavior such as the role of lignin in affecting ignition and burning behavior, or how the size of particles changes smoldering propagation rates. As a result of considering the influence of individual aspects of the fuels, knowledge gained from this study can be applicable to a wide range of fuels and conditions encountered in nature. Hence, we expect that knowledge gained from this work can be applicable to nearly all fuels of interest to the DoD.

The third implication of this work is a model for smoldering of general real fuels that was used to examine the impact of composition, moisture content, and density on smoldering ignition and behavior. This model is openly available and described in detail in publications resulting from the project, and can be used by the community to examine smoldering of particular fuels based on composition. This is in contrast using a model validated for a specific fuel. In addition, we extracted simple empirical models for smoldering ignition, temperature, and propagation speed

as functions of composition that can be used by practitioners to quickly estimate smoldering-related risks.

A fourth major implication of this work was pioneering the use of surrogate fuels to emulate key characteristics of natural fuels. Prior works have considered surrogate fuels for other complicated fuels (e.g., jet fuels, diesel [30–32]), but the use of surrogate fuels to understand and predict smoldering combustion has not been widely considered. A surrogate fuel is a simplified fuel that emulates key features of (typically more complicated) natural materials (e.g., burning rate, peak temperatures). An advantage of using surrogate fuels is calculations are more tractable and arguably can better capture key physical and chemical processes. Equally important, the use of surrogate fuel has the potential to allow smoldering behavior to be predicted a priori if the constituents and properties of the fuel bed are known. Certainly, additional analysis is needed to further evaluate the usefulness/limitations of surrogate fuels to study or predict smoldering behavior. Nonetheless, the methodology and approach to considering smoldering of fuels considered in this study are expected to greatly influence how smoldering research is conducted and analyzed and new fuels are considered.

The fifth major implication of this project is further understanding the role of heat transfer in controlling/influencing smoldering behavior. We believe that the critical role of heat transfer in controlling smoldering behavior has not been thoroughly appreciated. As noted earlier, experiments were systematically performed where fuels of differing particle sizes were burned. We expected that larger particles would burn more quickly because of the greater oxygen availability (in the pores between particles). In contrast, reducing the size of particles resulted in faster horizontal propagation rates despite having more fuel to burn within a volume and presumably reduced oxygen availability between the particles. Heat transfer analysis showed that smaller particles more readily transfer heat between particles whereas larger particles can be more sensitive to losses caused by natural convection. We expect that this new fundamental insight will be used by the smoldering community to greatly enhance how we explain and understand smoldering.

6.8 Suggested Future Work

- The concept of using surrogate fuels when modelling or predicting smoldering behavior of natural fuels can use further analysis and validation. If the validity of the approach is proven, it can enable more readily modeling smoldering behavior of new fuels without requiring extensive experimental campaigns. Additional analysis should consider and compare additional natural and surrogate fuels. The (limited) results obtained in this study were inconclusive. In addition, the physical characteristics of the fuel (e.g., spacing, cracks, density) should ultimately be considered when developing surrogates of natural fuels.
- The detailed computational model that was developed can be extended to two- and three-dimensions and consider gas phase characteristics. The additional computational ability can be used to better predict the transition from flaming to smoldering combustion and provide insights into the controlling physical processes. In addition, this more detailed model can be used to develop improved reduced order models.
- The smoldering characteristics from additional natural fuels should be measured. The results from burns of Douglas-fir and ponderosa pine duff indicate that the smoldering behavior is relatively similar. Experiments using duff from other vegetation could be used to better understand the applicability/limitations of the results to multiple/all species.
- The role of wind in influencing smoldering behavior and the transition from smoldering to flaming combustion needs further research. Some knowledge is available in literature, but notable knowledge gaps remain.

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8. Appendices

A.1 Supporting Data

Table A.1. Statistics for linear regression of EF versus MCE

EF	N	intercept	slope	r	p-value
C ₂ H ₆	80	-0.12	1.70	0.09	4.38E-01
C ₂ H ₄	80	0.52	0.73	0.04	7.04E-01
C ₂ H ₂	80	-4.70	6.26	0.55	1.22E-07
C ₃ H ₈	80	-2.05	3.67	0.25	2.58E-02
C ₃ H ₄	80	-0.93	1.35	0.36	1.14E-03
iso-butane	80	1.11	-1.30	-0.72	3.33E-14
butane	80	2.56	-2.95	-0.63	4.22E-10
tert-butene	80	1.86	-2.06	-0.49	3.92E-06
butene	80	2.85	-3.10	-0.49	4.84E-06
iso-butene	80	-1.65	2.31	0.40	2.55E-04
cis-butene	80	-0.32	0.48	0.33	2.84E-03
butadiene	80	-0.14	0.31	0.14	2.25E-01
iso-pentane	80	0.62	-0.63	-0.31	4.92E-03
pentane	80	0.12	-0.06	-0.04	7.13E-01
cis/trans-pentene	80	1.11	-1.26	-0.53	4.33E-07
pentene	80	-0.14	0.29	0.12	2.71E-01
cis/trans-pentene	80	-0.39	0.57	0.31	5.59E-03
hexane	80	0.85	-0.95	-0.48	6.72E-06
1-hexene	80	1.07	-1.22	-0.35	1.25E-03

A.2 List of Scientific and Technical Publications

A.2.1 Articles in peer-reviewed journals (specify whether in print, accepted for publication, or submitted for publication)

1. D. Cowan, W. Page, B. Butler, D. Blunck, “Effects of Fuel Characteristics on Spread Rate and Surface Temperatures of Smoldering Duff,” *International Journal of Wildland Fire*, Vol. 29 pp. 820-831 (2020).
2. B. Smucker, T. Mulky, D. Cowan, K. Niemeyer, D. Blunck, “Effects of Fuel Content and Density on the Smoldering Characteristics of Cellulose and Hemicellulose,” *Proceedings of the Combustion Institute*, Vol. 37, pp. 4107-4116 (2019).
3. A. Ross, D. Blunck, “Influence of particle sizing on smoldering behavior,” manuscript drafted.
4. A. Ross, D. Blunck, “Effects of Fuel Characteristics on Spread Rate and Surface Temperatures of Smoldering Douglas-fir Duff,” In preparation for submission to *IJWF*.
5. B. Smucker, J. Jayasuriya, K. Niemeyer, D. Blunck, “Influence of Lignin on Smoldering Propagation”, In preparation
6. W. Jayani Jayasuriya and Kyle E. Niemeyer. “A computational investigation into the ignition of smoldering combustion.” In preparation.
7. Tejas C. Mulky, W. Jayani Jayasuriya, and Kyle E. Niemeyer. “Smoldering combustion in cellulose and hemicellulose mixtures: Examining the roles of density, fuel composition, oxygen concentration, and moisture content.” 2021, under review.
8. Jeffrey F. Glusman, Kyle E. Niemeyer, Amanda S. Makoweicki, Nicholas T. Wimer, Caelan B. Lapointe, Gregory B. Rieker, Peter E. Hamlington, and John W. Daily. 2019. “A Reduced Gas-Phase Kinetic Model for Burning of Douglas Fir.” *Frontiers in Mechanical Engineering*, 5:40. <https://doi.org/10.3389/fmech.2019.00040>
9. Tejas C. Mulky and Kyle E. Niemeyer. 2019. “Computational study of the effects of density, fuel content, and moisture content on smoldering propagation of cellulose and hemicellulose mixtures.” *Proceedings of the Combustion Institute*, 37(3):4091–4098. <https://doi.org/10.1016/j.proci.2018.06.164>

A.2.2. Conference or symposium proceedings scientifically recognized and referenced (other than abstracts)

1. A. Ross, H. Boriyo, C. Flaherty, M. Hilliker, D. Blunck, “The Influence of Wind Speed on Smoldering Behavior of Cellulose,” *12th U.S. National Combustion Meeting*, College Station, TX, (2021).

2. A. Ross, D. Blunck, “The Influence of Heat Transfer and Oxygen Availability on Smoldering Behavior Through a Porous Fuel,” *12th U.S. National Combustion Meeting*, College Station, TX, (2021).
3. B. Smucker, D. Blunck, “The Efficacy of Surrogates to Estimate Smoldering Behavior of Natural Fuels,” *12th U.S. National Combustion Meeting*, College Station, TX, (2021).
4. D. Cowan, D. Blunck, “Effects of Fuel Characteristics on Spread Rate and Surface Temperatures of Smoldering Duff,” *11th U.S. National Combustion Meeting*, Pasadena, CA, (2019).
5. B. Smucker, W. Jayasuriya, K. Niemeyer, D. Blunck, “Influence of Lignin on Smoldering Propagation” *11th U.S. National Combustion Meeting*, Pasadena, CA, (2019).
6. B. Smucker, D. Cowan, D. Blunck, “Effects of Fuel Composition and Packing Density on Horizontal Smoldering Propagation,” *Western States Section of the Combustion Institute Meeting*, Laramie, WY (2017).
7. D. Cowan, B. Smucker, D. Blunck, “Sensitivity of Smoldering Combustion to Cellulose and Hemicellulose Content,” *10th US Combustion Meeting*, College Park, MD (2017).
8. W. Jayani Jayasuriya and Kyle E. Niemeyer. “Smoldering combustion of cellulose, hemicellulose, and lignin: Investigating the roles of fuel composition, density, oxygen concentration and moisture content.” 2019 Fall Technical Meeting of the Western States Section of the Combustion Institute, Albuquerque, NM, USA. 14–15 October 2019.
9. Jeffrey F. Glusman, Amanda S. Makoweicki, Nicholas T. Wimer, Kyle E. Niemeyer, Gregory B. Rieker, Peter E. Hamlington and John W. Daily. “A chemical kinetic model reduction and pyrolysis model for wildland fire direct numerical simulation.” 2018 Spring Technical Meeting of the Western States Section of the Combustion Institute, Bend, OR, USA. 26–27 March 2018.
10. W. Jayani Jayasuriya, Tejas C. Mulky, and Kyle E. Niemeyer. “Modeling smoldering of real fuels in wildland fires.” 17th International Conference on Numerical Combustion, Aachen, Germany. 6–8 May 2019.
11. Tejas C. Mulky and Kyle E. Niemeyer. “Preliminary analysis of smoldering combustion in cellulose and hemicellulose mixtures.” 2017 Fall Technical Meeting of the Western States Section of the Combustion Institute, Laramie, WY, USA. 2–3 October 2017.

A.2.3 Conference or symposium abstracts

Poster: *Forest Fire Smoldering Emissions from Ponderosa Pine Duff in Central Washington*

Stephen P. Baker, Emily N. Lincoln, Megan J. Richardson, Wesley Page
American Geophysical Union Fall Meeting, December 2017

A.2.4 Thesis or Dissertations

Tejas Mulky, Computational study of smoldering combustion in cellulose and hemicellulose mixtures, MS Thesis, Mechanical Engineering, Oregon State University, Sep.

2018. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/mk61rp01r

Daniel Cowan, Effects of Fuel Characteristics on Spread Rate and Surface Temperatures of Smoldering Duff, MS Thesis, Mechanical Engineering, Oregon State University

Andrew Ross, The Influence of Fuel Characteristics on Smoldering Behavior through Porous Fuels, MS Thesis, Mechanical Engineering, Oregon State University

Current PhD Students (expected to defend dissertation in 2022)

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