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Piloted ignition of live forest fuels[☆]

S. McAllister^{*}, I. Grenfell, A. Hadlow, W.M. Jolly, M. Finney, J. Cohen

Missoula Fire Sciences Laboratory, USDA Forest Service, 5775W US Highway 10, Missoula, MT 59808, USA

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ABSTRACT

The most unpredictable and uncontrollable wildfires are those that burn in the crowns of live vegetation. The fuels that feed these crown fires are mostly live, green foliage. Unfortunately, little is known about how live fuels combust. To understand how live fuels burn, piloted ignition experiments were performed with lodgepole pine and Douglas-fir. The thermal behavior (thick versus thin) of both live and dead needles was explored. Both live and dry needles were shown to behave as thermally intermediate solids in this apparatus. Additionally, samples were collected throughout the growing season to take advantage of the natural variation in moisture content and chemical composition. This data set was then compared to several correlations found in the literature to determine whether live fuel ignition can be predicted by moisture content alone and to test the applicability of these models to the wildland fire problem. Many of the correlations from the literature for ignition time with moisture content fail to capture the trends with live fuels. A linear regression of the ignition time with moisture content only predicts 74–80% of the variability suggesting that there is another mechanism controlling ignition time of live fuels. Based on the hypothesized difference in water storage between live and wet dead fuels, the chemical composition of the live needles was included in an empirical model for ignition time. Including chemical composition improved the prediction accuracy for Douglas-fir needles only. Because the thermal properties of live foliage are largely unknown, it is possible that the predictions from more physically-based models would show improvement with more accurate values of density, thermal conductivity, and specific heat.

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1. Introduction

The most unpredictable and uncontrollable fires are those that burn in the crowns of live vegetation. The fuels that feed these crown fires are mostly live, green foliage. Unfortunately, little is known about how live fuels combust. For decades, live fuels were simply treated as wet dead fuels and the moisture content was assumed to determine its fire behavior [1–6]. However, very little work has been done to justify this assumption. Only a few known studies on live fuels have been performed [7–10]. Xanthopoulos and Wakimoto [7] convectively heated live fuels to ignition and generated empirical correlations for ignition time with moisture content for ponderosa pine, lodgepole pine, and Douglas-fir. Dimitrakopoulos and Papaioannou [8] performed similar experiments in a cone calorimeter to derive their own set of empirical correlations for ignition time with moisture content for common Mediterranean vegetation. However, the applicability of empirical models to different species and conditions is suspect. Predictions

of ignition times are needed that only depend on material properties. Smith [9] attempted to include more physical reasoning in his correlations for convectively ignited foliage from chaparral and native Utah vegetation by starting with a “modified lumped capacitance” model. However, Smith is still left with species-specific constants in his correlations that must be determined experimentally. Other correlations developed primarily for wet wood and other cellulosic materials exist in the literature. These include Pickard and Wraight [11], Simms and Law [12], Babrauskas [13], Moghtaderi [14], and Khan et al. [15]. Recently, Jervis et al. [10] have compared the burning behavior (both ignition and heat release rate) of live and dead pine needles. They showed that though much of the differences between live and dead fuels can be explained by changes in moisture content, there were other physical and chemical differences that should be further explored.

Water affects ignition in both the solid and gas phase processes. If all of the water within the fuel does not evaporate prior to ignition, then the water vapor will dilute the gaseous pyrolyzates making it more difficult to generate a flammable mixture [13]. In fact, Janssens showed in [16] that the ignition temperature increased by about 2 °C for each percent increase in moisture. Atreya and Abu-Zaid found a similar result in [17] for

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^{*} Corresponding author.

E-mail address: smcallister@fs.fed.us (S. McAllister).

Nomenclature		Subscripts	
c	specific heat (kJ/kg)	b	boiling
d	thickness (m)	ig	ignition
Δh_{vap}	heat of vaporization of water (kJ/kg)	0	initial or dry property
k	thermal conductivity (kW/mK)		
MC	moisture content (dimensionless)		
t	time (s)		
T	temperature (K)		
<i>Greek letters</i>			
α	absorptivity (dimensionless)		
ρ	density (kg/m ³)		

moisture contents up to about 30%. As detailed in [12], water has three effects on the solid: it changes the thermal properties of the material (density, thermal conductivity, and specific heat), it transfers heat by molecular diffusion, and its evaporation is strongly endothermic. There seems to be some disagreement in the literature about whether moisture content has a stronger effect on the solid phase or the gas phase. In [13], Babrauskas claims the gas phase effect to be a minor in comparison to the solid phase effects. However, in [18] Abu-Zaid claims that the increase in ignition temperature with moisture content is more important than the change in the solid thermal properties. An important point to consider is that the fiber saturation moisture content for wet dead woody fuel is only about 30% [19]. Live fuels can have moisture contents of over 250%, making it likely that a significant amount of water is still being released from the fuel at ignition and that the mechanisms that control ignition could be different for live versus wet dead fuels.

A still unexplained empirical observation is that of the “moisture of extinction” [3]. Wildland fires in dead fuels will not spread above some threshold of fuel moisture content, typically assumed to be between 10% and 40% [3]. However, in crown fires, live fuels with moisture contents well above 70% are what carry the extremely vigorous fire. One possible explanation proposed here is that this behavior is due to the different physical manner in which live and dead fuels can store water. In a dead fuel, the water is adsorbed into the cell walls. When heated, this water evaporates and diffuses out from the material. In contrast, much of the water in a live fuel is stored within living cells. As a live fuel is heated, it is possible that the water is not simply released due to evaporation, but in more of an “explosive” process as the cell walls burst. This expulsion of aqueous cell contents would be much more rapid than the relatively slow diffusion of moisture through dead plant tissues. During the experiments reported here, the live needles would audibly “pop” and would often “jump” around inside the sample holder during the rapid heating process just prior to ignition. Because much of the water released from a live fuel may be through this “explosive” process, it may also carry with it some of the sugars stored within the cells or even cell walls themselves. About half of the mass of a live fuel is non-structural carbohydrates, the sugars and starches that the plant produces by photosynthesis. It is possible that these presumably flammable non-structural carbohydrates can compensate for the dilution of the pyrolyzates by water vapor at ignition and allow live fuels to burn at much higher moisture contents than dead fuels.

In this study, we examine the ignition behavior of two species of live fuels, Douglas-fir (*Pseudotsuga menzeseii*) and lodgepole pine (*Pinus contorta*). First, the thermal behavior (thermally thick or thin) of both live and dry needles is explored. To provide further insight into the thermal behavior, the evolution of the

water concentration in the evolved gases is measured during the entire heating process to determine whether water is still evaporating at the moment of ignition. The ignition delay time is then measured over an entire growing season to take advantage of the natural variation in moisture content and chemical composition. These new data are compared to many of the correlations found in the literature for predicting ignition time based on moisture content. As there is currently no predictive capability for live fuel ignition, the goals of this comparison are two-fold: to determine whether the ignition time of live fuels can be predicted by moisture content alone and to determine the generality and applicability of these models to the wildland fire problem as a first estimation. The chemical composition of the fuels was also considered as an attempt to explain the discrepancies.

2. Experimental description

Because wildland fires can produce a wide range of heat fluxes and are very often associated with high winds (due to both weather and in-drafts to the fire), an apparatus was built to measure the ignition time and critical mass flux (CMF) for sustained flaming ignition of woody materials under these varying environmental conditions (heat flux and airflow velocity). Although the critical mass flux was not used for this analysis, future research will explore the relationship between CMF, moisture content, and needle chemistry. This apparatus, based on the Forced Ignition and Flamespread Test [20–24], consists of a small-scale wind tunnel, infrared heater, coiled wire igniter, and a high precision mass balance (see Fig. 1). The tunnel is 9 cm tall, 25 cm wide, and 60 cm long. A fan at the entrance produces a laminar forced airflow through the tunnel with a velocity ranging from 0.8 to 1.6 m/s (corresponding to Reynolds numbers of $3\text{--}6 \times 10^4$, well under the transition to turbulent flow).

The sample holder, measuring 9 cm \times 9 cm with a depth of 2.5 cm, is a thin, lightweight aluminum box lined with Cotronics¹-brand ceramic paper and a 1.27 cm thick Cotronics-brand ceramic board on the bottom. The sample holder sits on top of the mass balance with the upper surface of the sample flush with the bottom of the tunnel. The sample is heated from above using an infrared heater capable of producing a uniform heat flux of 0–50 kW/m² over the sample surface.

As the sample is heated, pyrolysis begins. The forced flow pushes the pyrolysis gases into the coiled Kanthal¹ wire igniter that initiates ignition. To remove the igniter location as a potential variable in the

¹ Business and trade names used for reference and do not constitute official endorsement.

experiments, the 3.5 mm diameter igniter is fixed 1.2 cm downstream of the sample, centered 6 mm off the bottom, a position which covers the fuel concentration boundary layer. Additionally, the igniter consisted of a fixed number of coils and the supplied current was calibrated to keep the igniter above 1000 °C. The time to ignition is recorded visually as the time from the initiation of heating until a flame is sustained over the surface of the sample. All tests are repeated three times to provide an estimate of the experimental variability.

Tests were performed with two species: lodgepole pine (*P. contorta*) and Douglas-fir (*P. menzeseii*). Small branches were cut from the lower sections of the trees and brought into the laboratory. Care was taken to minimize transpiration losses by keeping the branches intact and out of the sun and heat. The needles were cut from the branch, only taking healthy-looking needles from the previous year's growth. All needles were cut above the cuticle where the needle attaches to the branch to minimize the dead material. Because of the length of the needles, no further cutting was necessary to fit them into the sample holder. The lodgepole pine and Douglas-fir samples were 6 g and 4 g, respectively, and were weighed within 0.05 g. The sample size was chosen to ideally fill the entire sample holder with a single layer of needles. When placed into the sample holder, sheets of ceramic paper were used to support the needles such that they were flush with the surface of the sample holder and all samples were arranged to cover as much surface area as possible. For comparison purposes and to calculate

the surface area for the critical mass flux for ignition (not reported here), photographs were taken of the arrangement of each sample. For example, see Fig. 2. Because the color of the background can affect the ignition time of naturally colored needles, only tests with a similar “gray” background were included in the results. This variation with background color was not seen however when the needles were coated in graphite powder.

To evaluate the thermal behavior, ignition experiments were performed with both live and dry needles over a range of external radiant heat fluxes from 20 to 50 kW/m² with a constant airflow velocity of 1 m/s. The temperature of the halogen/quartz bulbs in the radiant heater varies with power output (from about 2389 K to 2820 K), so following the Planck distribution, the peak wavelength of the radiant energy varies from 1.213 μm at 20 kW/m² to 0.955 μm at 50 kW/m². Because vegetation shows spectral absorptivity, particularly for wavelengths below 2.8 μm [25,26], the needles were coated in a thin layer of graphite powder. All samples for this series of tests were collected on the same day from the same tree to minimize moisture content and chemical composition variability. The live samples were all burned the same day, while the dry needles were dried in an oven at 80 °C for at least 48 h prior to being burned. Eighty degrees Celsius was chosen because it was a high enough temperature to drive off the water, yet low enough to hopefully avoid driving off much of the low-temperature volatiles (see for example [27]).

To provide further insight into the thermal behavior, a LI-COR (Model #LI-7000¹) CO₂/H₂O analyzer was used to measure the release of water during the entire ignition process as a function of time. The inlet was placed 2.5 cm downstream of the sample and 1.7 cm off the surface of the tunnel. A pump running at 4 L/min pulled the gaseous sample through the LI-COR analyzer. The sample tube was heated with heat tape to prevent condensation within the tube. Due to the length of the sampling tube, there is a 1 s time lag in the readings. This was determined by the comparing the time of the spike in the sample mass loss with the time of the spike in water and carbon dioxide concentrations.

Seasonally, physiological processes can alter both the moisture content of leaves and the types of chemical compounds found in them. Advantage was taken of this natural seasonal variation in moisture content and chemical composition. For much of the growing season (March–October), weekly samples from both species were gathered and processed the same morning. The sample site (location, aspect, etc.) was the same each week, but different trees were sampled from week to week. Once removed from the branches, seven samples of each species were weighed, three to be burned immediately (“live” samples) and four to be dried in the oven at 80 °C for at least 48 h prior to being burned (“dry” samples). An additional 20 g was weighed for the chemical

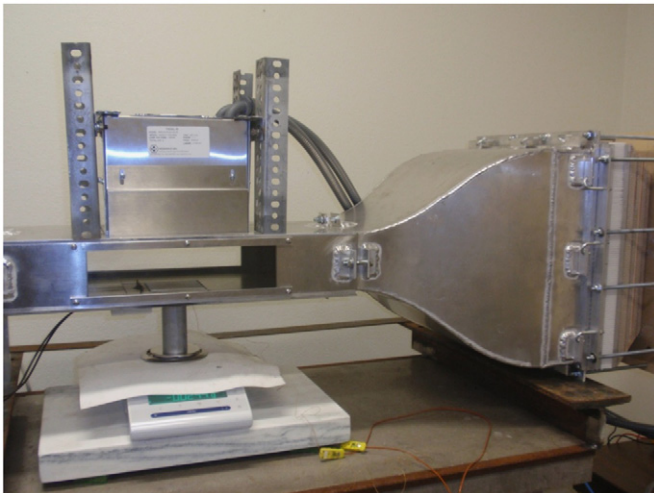


Fig. 1. Experiment apparatus: small-scale wind tunnel with high precision balance.



Fig. 2. Lodgepole pine (left) and Douglas-fir (right) samples.

analysis. To mimic the wind and high heat fluxes associated with a wildfire, all tests were performed with a fixed airflow velocity of 1 m/s and an irradiance of 50 kW/m². Though wildfires typically produce radiant heat fluxes in the range of 50–250 kW/m² [28,29], an irradiance of 50 kW/m² was chosen for these tests because it is the maximum attainable with this apparatus. It was necessary to get a rough estimate of the absorptivity of the needles at this heat flux because the values vary widely in the literature (from 0.33 to 1 [30]). A set of experiments was thus performed with the needles coated in a thin layer of graphite powder. The absorptivity was then roughly estimated as the ratio of the ignition times of the uncoated and coated needles.

Leaf chemical composition was determined using the wet reference method by an external forage testing laboratory (AgriAnalysis¹). The analysis provided measurements of neutral detergent fiber (NDF), crude fat (CF), crude protein (CP), and ash content (AC). Non-fiber carbohydrates (NFC) were calculated by the difference method:

$$\text{NFC} = 100 - \text{NDF} + \text{CF} + \text{CP} + \text{AC} \quad (1)$$

Neutral detergent fiber quantifies the structural carbohydrates such as cellulose, hemicellulose and lignin, while non-fiber carbohydrates are generally water soluble and represent primarily sugars, starches, and other non-structural carbon compounds in the needles. Also reported were the concentrations of acid detergent fiber (ADF=cellulose and lignin only) and the minerals calcium, phosphorus, potassium, and magnesium. Note that the non-moisture constituents will not add to 100% as cellulose and lignin are accounted for in both the NDF and ADF.

3. Results and discussion

3.1. Thermal behavior

The ignition delay times assuming thermally thick and thin behavior are plotted in Figs. 3 and 4 for both dry and live needles, respectively. As seen in Fig. 3, the influence of the substrate color on the thermal behavior was considered with the dry needles. As long as the needles are lightly coated with graphite powder, the color of the substrate does not influence the ignition time or the thermal behavior of the needles. Because no effect of the background color was seen, the thermal behavior of the live needles was evaluated with only a black-colored substrate. Though it is common for physically thin materials mounted on a substrate to behave as a thermally thick solid [13], it is estimated that this effect is minimal here because the needles typically do not sit flush on the substrate due to their curvature and thus only make minimal contact. Figs. 3 and 4 show that the ignition times of dry and live needles can be plotted equally well assuming thermally thick and thin behavior. Thus, both dry and live needles behave as a thermally intermediate solid in this apparatus. These results are in agreement with the modeling of Benkoussas et al. [31] which demonstrated that thin woody fuels in a wildfire may in fact be thermally thick. Despite being physically thin, the fine fuels typically consumed in a wildfire have low thermal conductivity, are subjected to high levels of heat flux, and typically experience simultaneous evaporation and pyrolysis, all tending to create large internal temperature gradients. In fact, Benkoussas et al. showed that the critical radius for thick and thin regimes of woody material in a 40 kW/m² heat flux is about 0.26 mm

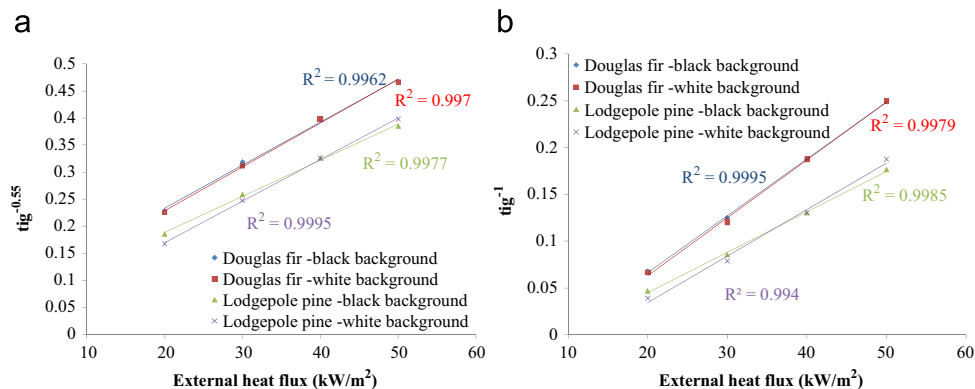


Fig. 3. Thermal behavior of dry needles with different substrate colors: (a) assuming thermally thick behavior and (b) assuming thermally thin behavior.

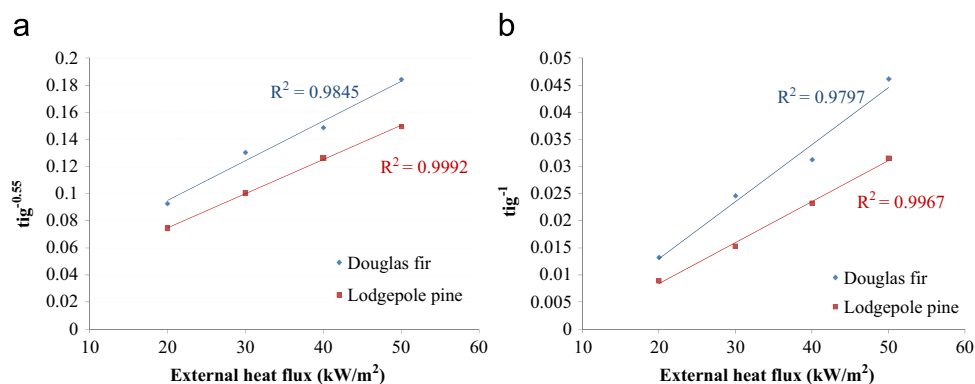


Fig. 4. Thermal behavior of live needles: (a) assuming thermally thick behavior and (b) assuming thermally thin behavior.

regardless of moisture content. If the needles tested here are considered cylinders, the radii of lodgepole pine and Douglas-fir needles are approximately 0.38 mm and 0.24 mm, respectively, which would indicate thermally-intermediate behavior.

To demonstrate that there are indeed temperature gradients in the fuel, the evolved gases from the fuel during heating and ignition were analyzed for the presence of water. Fig. 5 shows representative curves of water and carbon dioxide concentration in the evolved gases for lodgepole pine. The water concentration increases sharply as the sample is first heated due to evaporation from the needle surface. The water evolution peaks and begins to decrease just prior to ignition. At this point, the surfaces of the needles are at a sufficient temperature to pyrolyze, while the insides of the needles are still near the evaporation temperature, implying that there is a significant temperature gradient within the needles and that water is diluting the pyrolyzates. This finding agrees with [32] that demonstrated no significant evaporation occurred for heat fluxes greater than 35 kW/m².

3.2. Correlation of ignition time with moisture content

Fig. 6 shows the ignition time and moisture content variation over the course of the testing period with lodgepole pine on the left (Fig. 6a) and Douglas-fir on the right (Fig. 6b). The average standard deviation in ignition times were 4.5% for live lodgepole pine, 6.3% for live Douglas-fir, 7.8% for dry lodgepole pine, and 9.1% for dry Douglas-fir. The moisture content and ignition time for both live species exhibit a “u-shaped” trend during the growing season. The moisture contents and live fuel ignition times start out relatively high in March, then decrease during the spring months. The minimum in both moisture content and ignition time was seen at bud-break in about mid-June. The moisture content

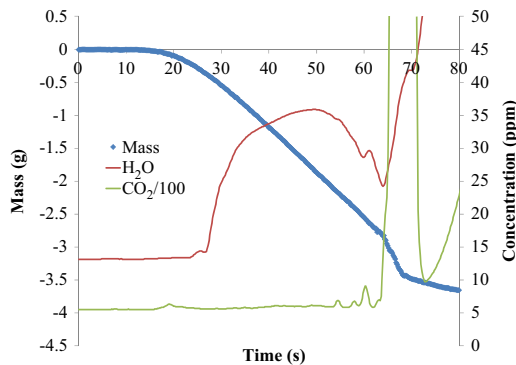


Fig. 5. LI-COR results of water and carbon dioxide concentrations compared to the change in mass during test. Ignition occurs at 63 s.

and live fuel ignition times then increase during the summer months and into fall. In general then, it qualitatively appears that the ignition time of live fuels is indeed strongly related to the moisture content.

This trend in moisture content may in part be due to the method traditionally used to determine moisture content. Moisture content is traditionally calculated as the difference between the wet and dry weight divided by the dry weight. However, this assumes that the dry weight remains constant which is, unfortunately, not the case with live fuels. As the growing season progresses, the dry mass of the live needles increases as the plant produces and stores sugars while preparing to grow new needles [33,34]. For this reason, it is possible that the apparent moisture content of live fuels will decrease early in the year, even if the water content never changes. The stored sugars get transferred to the new needles during and after bud break, decreasing the dry mass of the older needles which would increase the apparent moisture content. The moisture content of live needles is thus due to both changes in the water content and the dry mass [33–35].

Regardless of the cause of the changes in moisture content, the ignition time appears correlated to the moisture content. As discussed further, the ignition delay data measured here are compared to various correlations with moisture content found in the literature—linear regression following Dimitrakopoulos and Papaioannou [8] and Xanthopoulos and Wakimoto [7], and correlations and models from Moghtaderi [14], Simms and Law [12], Khan et al. [15], Pickard and Wraight [11], and Babrauskas [13]. The results of these comparisons are shown in Figs. 7 and 8.

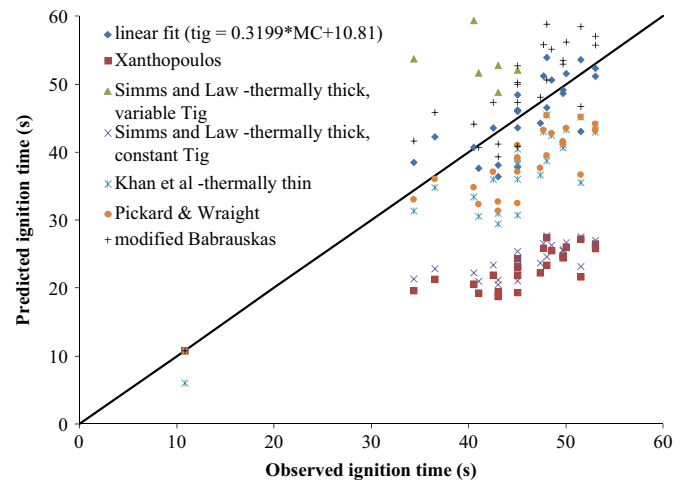


Fig. 7. Observed ignition times of lodgepole pine needles compared to those predicted by published ignition time models.

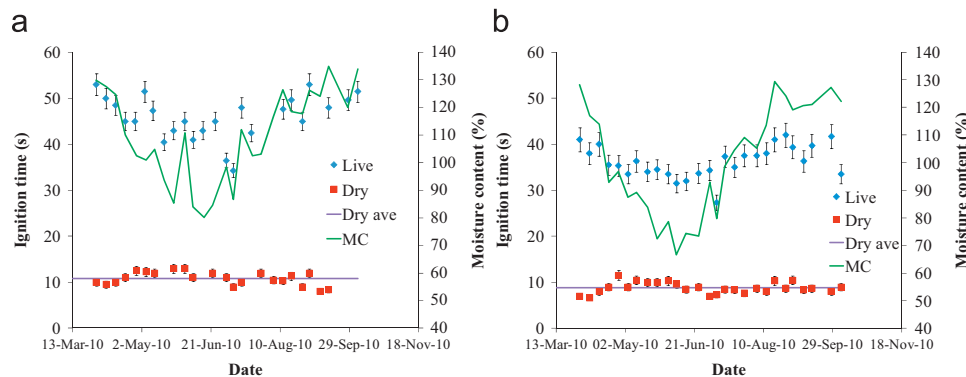


Fig. 6. Ignition time variation with time: (a) lodgepole pine and (b) Douglas-fir. The average standard deviation in ignition times were 4.5% for live lodgepole pine, 6.3% for live Douglas-fir, 7.8% for dry lodgepole pine, and 9.1% for dry Douglas-fir.

Though these models were developed for different experimental protocols and ranges of moisture content, they are being considered to develop a desperately needed first approximation for the ignition of live fuels.

3.2.1. Linear regression

To ascertain whether the ignition time of live fuels can be predicted by moisture content alone, a linear regression was applied to the data of both species as done by Dimitrakopoulos and Papaioannou [8] and Xanthopoulos and Wakimoto [7]. The results of this linear regression are shown in Fig. 9 where the intercept was fixed at the dry ignition time. The best linear fits to the data presented here have linear coefficients, intercepts, and coefficients of determination (R^2) values similar to the different species presented in [8] using a similar apparatus. The data were plotted by categorizing the data by season, with spring assumed to be March 30 through June 24, summer July 2 through September 8, and fall September 14 through October 5. Interestingly, the ignition times for the same moisture content can vary quite a bit (almost 30%), and can be dependent on the season. For example, the ignition time for live Lodgepole pine needles at approximately 85% moisture content was more than 10 s longer in the spring (May 25) than in the summer (July 7). By considering the linear regression of the entire data set, moisture content alone can only predict 74% and 80% of the variability in the ignition times for Douglas-fir and lodgepole pine, respectively. It is clear that there is some other variable affecting the ignition time of live fuels. Though not completely independent of moisture content, the

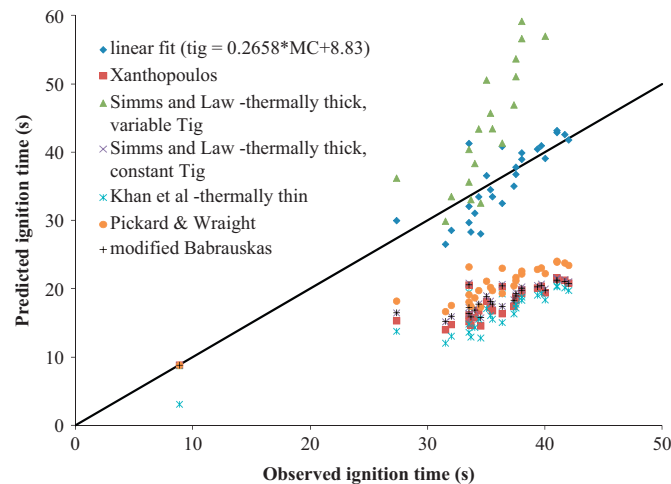


Fig. 8. Observed ignition times of Douglas-fir needles compared to those predicted by published models.

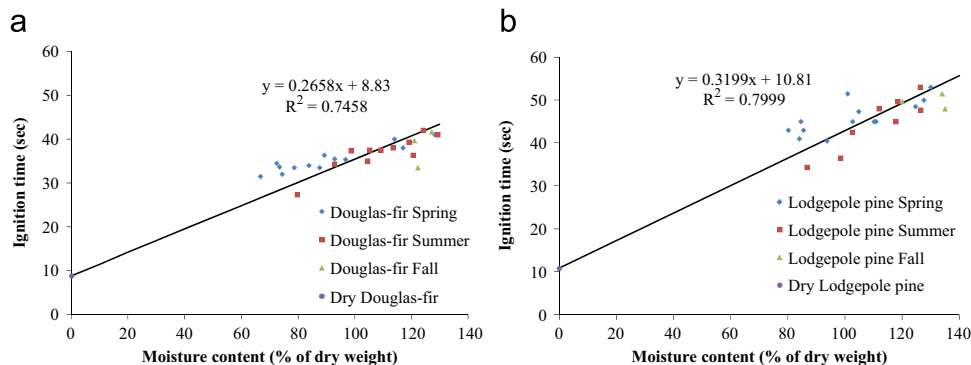


Fig. 9. Variation of ignition time with moisture content: (a) Douglas-fir and (b) lodgepole pine.

seasonal variation of the chemical composition is considered below as a possible explanation.

Xanthopoulos and Wakimoto give correlations for both species tested here, however, their test method was significantly different. Xanthopoulos and Wakimoto heated and ignited their samples convectively so that the heat transfer term in their correlations contains the temperature of the convective flow, for example $t_{ig} = c_1 \exp(c_2 T + c_3 MC)$, where c_i are species-specific constants, T is the convective flow temperature, and MC is the moisture content. In order to apply their correlation, the convective flow temperature was chosen to match the ignition time of the dry samples (492 °C for lodgepole pine and 473 °C for Douglas-fir). It is no surprise then that their correlations poorly predict the present data as shown in Figs. 7 and 8, emphasizing that empirical correlations cannot be reliably applied outside of the conditions in which they were generated.

Another consideration to be made is that there are no data for the transition between wet dead fuels and live fuels (moisture contents between 0% and about 65%). Because of the different nature of water storage between wet dead and live fuels, it is possible that the ignition times in this moisture content range could diverge from the linear fit shown in Fig. 9. The data could be better predicted by two linear fits – one for wet dead and one for live fuels – with a step-change or some other unknown function between them. Further work is needed to fill in this range of moisture contents.

3.2.2. Moghtaderi correlation

In [14], Moghtaderi fit his ignition data with a correlation that is quadratic in moisture content:

$$t_{ig,MC} = t_{ig,dry}(1 + 0.035MC)^2 \quad (2)$$

However, the data presented here do not show such a strong dependence on moisture content and this correlation grossly overpredicts ignition time for live fuels. The predicted ignition times from this model are therefore not seen in Figs. 7 and 8. Though this correlation is inappropriate for use with live fuels, this correlation may, however, capture the “moisture of extinction” seen for dead fuels.

3.2.3. Simms and Law correlation

Simms and Law argued in [12] that the variation in ignition time with moisture content could be explained solely by the variation of the material properties. In [12] they provide relations for the variations in density, thermal conductivity, and specific heat with moisture content. However, these relations require knowledge of these properties for the dry fuel. These properties are well measured for wood, but very little exists in the literature for values of the needles. In this work, the thermal conductivity

Table 1

Thermal properties. Thermal conductivity, specific heat, and ignition temperature are assumed to fit the dry fuel ignition time.

	Dry wood [source]	Assumed lodgepole pine (dry) [source]	Assumed Douglas-fir (dry) [source]
Thermal conductivity, k (kW/mK)	1.25–1.85 $\times 10^{-4}$ [13]	1.69 $\times 10^{-4}$ [assumed]	1.85 $\times 10^{-4}$ [assumed]
Density, ρ (kg/m ³)	310–810 [13]	567 [1]	550 [1]
Specific heat capacity, c (kJ/kg K)	1.8 [13]	1.8 [assumed]	1.8 [assumed]
Effective, $k\rho c$ (kJ ² /m ⁴ s K ²)	0.068–0.91 [13]	NA	NA
Ignition temperature, T_{ig} (°C)	287–364 [13]	320 [assumed]	355 [assumed]
Adsorptivity, α (dimensionless)	0.33–1 [30]	0.576 [measured]	0.699 [measured]
Thickness, d (mm)	NA	0.76 [measured]	0.48 [measured]

and specific heat for the dry needles were chosen to fit the ignition time of the dry needles while constrained within the range found in the literature for wood. The material properties used are shown in Table 1 with the corresponding range of values from wood.

To predict the ignition time, these material properties were used with a standard ignition time equation for a thermally thick solid, e.g. from [36] or [37]. As discussed earlier, despite being physically thin, fine forest fuels can behave as thermally intermediate solids and thus can be described using either the thermally thick or thin assumption. For the correlation used here, the ignition time of the needles is best predicted here using the thermally thick assumption with Simms and Law's expressions for thermal properties.

Standard ignition time models also require the estimation of the ignition temperature. The ignition temperatures of the dry materials were estimated from the range found in the literature ($T_{ig}=296$ °C from [38], $T_{ig}=320$ °C from [3], up to $T_{ig}=346 \pm 40$ °C for $\dot{q}_e''=8$ –125 kW/m² from [39]) to fit the dry ignition data (see Table 1). If the ignition temperature is kept constant with moisture content, the ignition times are underpredicted using Simms and Law's model. It must be considered that the variation in material properties was calculated to fit wood species, however, it seems apparent that solid phase effects are insufficient to explain the increase in ignition time with moisture content.

To attempt to include the gas-phase effect, the variation in ignition temperature with moisture content was estimated using Janssens' result from [16] that the ignition temperature increases 2 °C for each percent moisture increase. This, however, leads to a much sharper increase in ignition time with moisture content than was measured and thus overpredicts the ignition time, particularly with the lodgepole pine needles. Because ignition temperature and some of the material properties of the needles are essentially unknown, it is possible that further exploration into these properties will result in improved correlations using this method. Additionally, it may be possible that the “explosive” release of moisture in live fuels results in a different effect of moisture on the ignition temperature than what is seen for dead fuels.

3.2.4. Khan et al. correlation

In [15], Khan et al. follow a similar approach as Simms and Law for ignition of wet corrugated paperboard. By including a term in the ignition delay expression that accounts for the variation of the material properties with moisture content, they obtain:

$$t_{ig,thin} = \frac{\rho_o c_o [1 + \gamma(MC/100)] d (T_{ig} - T_o)}{\alpha_s \dot{q}_e'' - \dot{q}_{loss}''} \quad (3)$$

$$t_{ig,thick} = \frac{\pi k_o \rho_o c_o [1 + 8.1(MC/100)] (T_{ig} - T_o)^2}{(\alpha_s \dot{q}_e'' - \dot{q}_{loss}'')^2} \quad (4)$$

where

$$\gamma = \frac{c_{water}(T_b - T_o) + \Delta h_{vap}}{c_o(T_{ig} - T_o)} \quad (5)$$

Using the properties in Table 1, the ignition time was predicted using both the thermally thick and thin assumptions. The thermally thin results are shown in Figs. 7 and 8. In contrast to the model of Simms and Law, the ignition times are best predicted using the thermally thin assumption. As discussed above, live needles in this apparatus exhibit thermally intermediate behavior and thus tend to be described equally well by both thick and thin correlations. The treatment of the moisture content is different between the models of Khan et al. and Simms and Law, perhaps affecting which thermal behavior is a better fit to the data.

Khan et al.'s thermally thin model works reasonably well for the lodgepole pine; however, the ignition times are still underpredicted for Douglas-fir. As with the model of Simms and Law, this model was developed for a different materials and perhaps a more thorough exploration of the material properties of the needles and their variation with moisture content would improve the accuracy of the model. Including the increase in ignition temperature with moisture content does not improve the predictions of Khan et al.'s model. This may imply that Khan et al.'s description of the solid phase effects of water on ignition time may be more accurate than Simms and Law.

3.2.5. Pickard and Wraight correlation

Pickard and Wraight in [11] take a more physical approach to predicting the effect of moisture content on ignition time. In their model, they assume that ignition and evaporation are separate events and that ignition occurs after evaporation is complete. The ignition time of a wet material is then given as the sum of the evaporation time and the dry ignition time:

$$t_{ig} = t_{ig,dry} + \frac{\Delta h_{vap} d \rho_o MC}{\alpha_s \dot{q}_e''} \quad (6)$$

where $t_{ig,dry}$ is the dry ignition time, Δh_{vap} is the heat of vaporization of water, d is the thickness, ρ_o is the density of the dry material, α_s is the surface absorptivity, and \dot{q}_e'' is the externally applied heat flux. As discussed above, this assumption is not appropriate for live fuels due to the high moisture contents and heat fluxes expected in an actual fire. Despite this, Pickard and Wraight's model does a reasonable job predicting the ignition time of lodgepole pine in Fig. 7, but generally underpredicts the ignition time of Douglas-fir in Fig. 8. Here also, the assumed material properties in Table 1 were used so the fit of the model may benefit from improved measurements of the thermal properties.

3.2.6. Babrauskas correlation

In [13], Babrauskas proposed a modification to the model of Pickard and Wraight that would account for the moisture evolution at ignition. In this model, it is assumed that only a fraction of the moisture, a , is evaporated:

$$t_{ig} = t_{ig,dry} + \frac{a d \rho_o MC}{\alpha_s \dot{q}_e''} \quad (7)$$

where $a = 33,200(\dot{q}_e'')^{-2} - 8.7$. A modified version of the parameter a was tested here that includes the effect of the surface absorptivity: $a = 33,200(\alpha_s \dot{q}_e'')^{-2} - 8.7$. The original version of Babrauskas's

model underpredicts the ignition time for both species. As seen in Figs. 7 and 8, once the effect of surface absorptivity is included, the model does quite well for lodgepole pine, yet still underpredicts the ignition time for Douglas-fir.

3.2.7. Summary

The linear regression of the ignition time with moisture content predicted 74% and 80% of the variability of the ignition for the Douglas-fir and lodgepole pine needles, respectively. This can be considered the best possible match to the experimental results when including only moisture content in a model. However, a linear regression is purely empirical and cannot be applied to conditions outside of where it was developed. A more physically-based model is needed. By comparing the residuals of all the models above, the modified version of Babrauskas's model, where only a fraction of the moisture content was assumed to evaporate prior to ignition, is the most promising and warrants further exploration as to its applicability to wildland fires. Though the level of accuracy obtained from only considering moisture content is adequate for some applications, it is clear that there is another mechanism controlling the ignition of these live fuels. The next section considers the variation in chemical composition of the needles as a possible controlling mechanism for the ignition of live fuels.

3.3. Correlations of ignition time with MC and chemicals

A particularly puzzling phenomenon in wildland fires is that live fuels will readily burn at moisture contents twice that of the "moisture of extinction" for dead fuels. As seen above, moisture content only explains 74–80% of the variability of the ignition time of live fuels and that the ignition time can vary up to 30% for the same moisture content. Based on the hypothesis that live fuels are different from wet dead fuels because of the different mechanisms of water storage and release, the chemical composition of the live fuels was considered to help explain the ignition of live fuels. Fig. 10 shows the results of the chemical analysis for

both species for the entire testing period. In general, lodgepole pine had a higher moisture content and higher levels of protein, structural carbohydrates (both acid detergent fiber and neutral detergent fiber), magnesium, and fat compared to the Douglas-fir needles. The Douglas-fir needles had higher concentrations of calcium, phosphorus, potassium, and non-fiber carbohydrates. This chemical composition data were included in a linear regression model with moisture content. The statistically significant chemical species in predicting the ignition time were determined for both species and best linear fit regressions were found. The intercepts and linear coefficients for these best fit regressions are shown in Tables 2 and 3. Also included in these tables are the probabilities that the value is outside the range given (the smaller the number the better). Fig. 11 shows a visual representation of the fits of the lodgepole pine model (Table 2) and the Douglas-fir model (Table 3) to both the lodgepole pine (Fig. 11a) and Douglas-fir data (Fig. 11b).

Several interesting results were found during this procedure. Following the discussion of the trend in apparent moisture content earlier, many of the chemical species measured were statistically correlated with the moisture content (see Table 4) and are therefore not truly independent parameters. Also, the statistically significant chemical species in predicting the ignition time were not the same for both lodgepole pine and Douglas-fir. By comparing Tables 2 and 3, it is seen that moisture content and acid detergent fiber (cellulose and lignin) are the only two common parameters. It is not too surprising however that potassium and phosphorus are not important predictors for the lodgepole pine because these minerals did not vary in concentration much throughout the season (see Fig. 10). The sign of the coefficients change between species and models because of the colinearity between many of the chemical species and the moisture content.

Table 2

Linear regression coefficients for the best fit model to the lodgepole pine data. $t_{ig} = \text{Intercept} + c_1MC + c_2ADF$.

Lodgepole pine (adjusted $R^2 = 0.5567$)		
	Coefficient	Pr > t
Intercept	37.52508	0.000329
MC	0.22308	1.68e-05
Acid detergent fibers	-0.48050	0.085018

Table 3

Linear regression coefficients for the best fit model to the Douglas-fir data. $t_{ig} = \text{Intercept} + c_1MC + c_2\text{Protein} + c_3ADF + c_4P + c_5K + c_6NFC$.

Douglas-fir (adjusted $R^2 = 0.8085$)		
	Coefficient	Pr > t
Intercept	-30.01617	0.02126
MC	0.07409	0.03605
Protein	1.47592	0.03036
Acid detergent fibers	0.44407	0.04934
P	55.44064	0.00695
K	-13.09364	0.01003
NFC	0.68099	0.00016

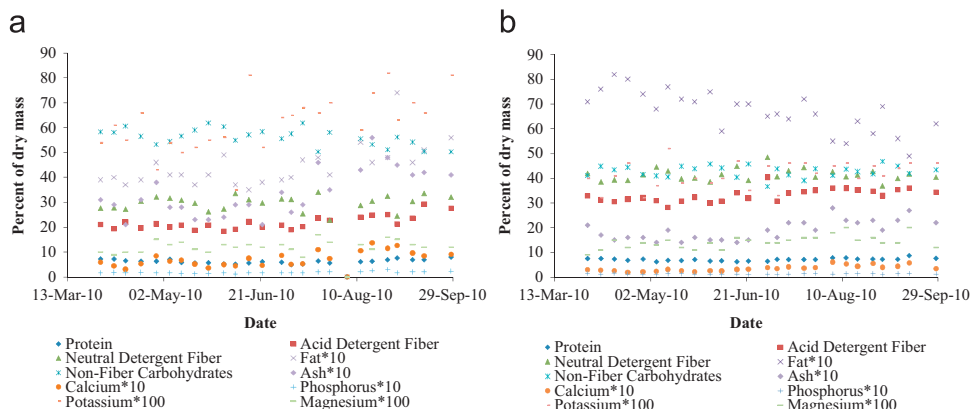


Fig. 10. Chemical analysis of live needles: (a) Douglas-fir and (b) lodgepole pine.

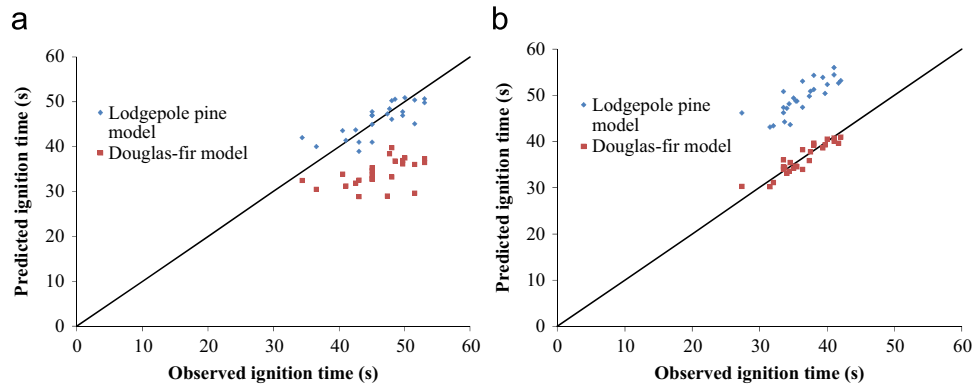


Fig. 11. Predicted ignition times compared to observed for both lodgepole pine model (Table 2) and Douglas-fir model (Table 3): (a) lodgepole pine data and (b) Douglas-fir data.

Table 4
Correlation of chemical species and moisture content.

	MC	Crude protein	ADF	NDF	Ca	P	K	Mg	Crude fat	Ash	NFC
Douglas-fir											
MC	1.0000	0.7443	0.6719	0.0070	0.6125	0.7283	0.5026	0.1316	0.5233	0.7147	-0.4735
Crude protein	0.7443	1.0000	0.5553	0.1862	0.4498	0.5002	0.3246	0.2186	0.5289	0.4983	-0.5446
ADF	0.6719	0.5553	1.0000	0.4465	0.6356	0.7509	0.5845	0.3921	0.5313	0.7432	-0.7776
NDF	0.0070	0.1862	0.4465	1.0000	0.2813	0.2630	0.0845	0.4201	0.0580	0.3592	-0.7895
Ca	0.6125	0.4498	0.6356	0.2813	1.0000	0.7243	0.5285	0.6384	0.6661	0.9436	-0.6905
P	0.7283	0.5002	0.7509	0.2630	0.7243	1.0000	0.7735	0.3722	0.4373	0.8018	-0.6329
K	0.5026	0.3246	0.5845	0.0845	0.5285	0.7735	1.0000	0.1623	0.3205	0.5343	-0.3747
Mg	0.1316	0.2186	0.3921	0.4201	0.6384	0.3722	0.1623	1.0000	0.4641	0.5396	-0.6519
Crude fat	0.5233	0.5289	0.5313	0.0580	0.6661	0.4373	0.3205	0.4641	1.0000	0.6571	-0.5105
Ash	0.7147	0.4983	0.7432	0.3592	0.9436	0.8018	0.5343	0.5396	0.6571	1.0000	-0.7790
NFC	-0.4735	-0.5446	-0.7776	-0.7895	-0.6905	-0.6329	-0.3747	-0.6519	-0.5105	-0.7790	1.0000
Lodgepole pine											
MC	1.0000	0.7548	0.2586	-0.2009	0.5154	0.5717	0.3158	0.2248	-0.2625	0.6913	0.0061
Crude protein	0.7548	1.0000	0.3121	-0.1867	0.6123	0.5193	0.2883	0.3475	-0.5274	0.7889	-0.0012
ADF	0.2586	0.3121	1.0000	0.5466	0.6663	0.1805	0.3802	0.4069	-0.6099	0.6165	-0.5451
NDF	-0.2009	-0.1867	0.5466	1.0000	0.2445	0.1205	0.4278	0.1946	-0.2940	0.2419	-0.9496
Ca	0.5154	0.6123	0.6663	0.2445	1.0000	0.4087	0.4940	0.7224	-0.8031	0.8510	-0.2606
P	0.5717	0.5193	0.1805	0.1205	0.4087	1.0000	0.6225	0.2879	-0.1929	0.5555	-0.2756
K	0.3158	0.2883	0.3802	0.4278	0.4940	0.6225	1.0000	0.3685	-0.3880	0.6263	-0.4826
Mg	0.2248	0.3475	0.4069	0.1946	0.7224	0.2879	0.3685	1.0000	-0.4803	0.4758	-0.2002
Crude fat	-0.2625	-0.5274	-0.6099	-0.2940	-0.8031	-0.1929	-0.3880	-0.4803	1.0000	-0.7014	0.2063
Ash	0.6913	0.7889	0.6165	0.2419	0.8510	0.5555	0.6263	0.4758	-0.7014	1.0000	-0.3679
NFC	0.0061	-0.0012	-0.5451	-0.9496	-0.2606	-0.2756	-0.4826	-0.2002	0.2063	-0.3679	1.0000

Table 5
Akaike Information Criterion values. Degrees of freedom (number of parameters in model) are in parentheses.

	Lodgepole pine	Douglas-fir
AIC—average t_{ig}	76.5987 (1)	66.93683 (1)
AIC—including MC	60.36414 (2)	40.80877 (2)
AIC—best with chemistry	58.89348 (3)	28.83288 (7)

The addition of the chemical composition results significantly improved the correlation of the Douglas-fir data only. The inclusion of the chemical composition only had a very minor effect on the correlation of the lodgepole pine data. Table 5 quantifies this using the Akaike Information Criterion (AIC) [40]. The AIC number based on the average ignition time serves as the baseline for comparing the models. As shown, the AIC shows quite an improvement (the lower the number the better) for both species when moisture content is included. For Douglas-fir, the AIC improves further with the inclusion of the chemical composition (model parameters from Table 3) but no change is seen for lodgepole pine (model parameters from Table 2).

4. Conclusions

To explore the piloted ignition of live fuels, experiments were performed with live and dry lodgepole pine and Douglas-fir needles. The thermal behavior of both live and dry needles was assessed and it was found that both live and dry needles behave as a thermally intermediate solid in this apparatus. To take advantage of the natural variation in moisture content and chemical composition, samples were collected and burned throughout the growing season. This data set was then compared to several correlations found in the literature to determine whether live fuel ignition can be predicted by its moisture content alone and to test the applicability of these models to the wildland fire problem as a first approximation. Many of the correlations for ignition time do not correctly capture the trend with moisture content and therefore are not applicable to the ignition of live fuels. This may be due to the different manner of water storage and release of moisture from a live fuel as compared to a dead fuel. The linear fit of data with moisture content explains 74–80% of the variation in ignition time, which may be adequate for some applications, but it is still empirical in nature. For a more physically-based model, the modified version

of Babrauskas's model, where only a portion of the moisture is assumed to evaporate before ignition, shows promise and warrants further exploration as to its applicability to wildland fires.

Because the thermal properties and dynamics of moisture loss of live foliage are largely unknown, it is possible that the predictions from the more physically-based models would show improvement with more accurate values of density, thermal conductivity, and specific heat. Choosing an appropriate model for live fuel ignition will also benefit from the evaluation of the importance of solid phase and gas phase effects for both wet dead and live fuels. The inclusion of chemical composition seems to be profitable for Douglas-fir, suggesting some influence of the different means of water storage of live fuels. Further exploration into the role of the chemical composition and explosive release of cell contents (and water) on ignition time is thus required.

Future work will involve testing at moisture contents between live and dead (0–65% moisture content), testing different species, and different test conditions (heat flux and oxidizer flow velocity) to develop a clearer picture of the trends. The effect of cutting the needles off of the branch will also need to be explored. The differences in ignition time between species are also unexplained. Experiments and modeling are required to determine whether the ignition time difference between species is due to the chemical composition of the needles or due to their structure (thickness, view factor to radiation source, etc.). These types of conclusions cannot be made with the current data because the structural variations were not controlled for nor were the sample sizes the same between species.

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