

Convection Ignition of Live Forest Fuels

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ABSTRACT

Wildland fires are an extremely costly and deadly problem. Crown fires, where live foliage ignites and burns, are particularly unpredictable – in part because live fuel ignition and combustion is poorly understood. Many wildland fire models assume radiation is the controlling heat transfer mechanism. However, there is a growing indication that radiation is insufficient to ignite the small, thin fuel particles that carry a wildland fire and that convective heating and flame bathing is a critical component. Unfortunately, ignition by convection heating of any fuel is poorly understood. Ignition of live forest fuels by any means is also completely unknown due to complicated moisture content and fuel chemistry considerations. To gain some insight into the wildland fire problem, an apparatus was built using two 6.5 kW electrical heaters to heat gas (air, nitrogen, etc.) over a range of temperatures from ambient up to 1200°C. The flow rate of these “airtorches” is adjustable. This apparatus was used to convectively ignite a range of both live and dead forest fuels. Fuels from all over the United States were used including Southern California, Utah, Florida, and Montana. To examine ignition threshold conditions and to have distinguishable differences in ignition times, air temperatures of 500°C and 600°C were used. The airflow rate varied slightly from 1.3 m/s to 1.4 m/s due to the density difference. Because live forest fuels contain large amounts of water, the evolution of both water and carbon dioxide was measured with time using a differential gas analyzer. Flaming ignition was seen for all dead fuels at 500°C, but the live fuels mostly showed glowing ignition. At 600°C, all fuels showed flaming ignition within 1-26 sec. Interestingly, all live fuels were still actively releasing water at ignition, implying there are steep temperature gradients within these physically thin fuels (i.e. not thermally thin). Simple heat transfer analysis in conjunction with the water evolution information was used to help explain the differences in ignition times due to fuel geometry.

KEYWORDS: wildfires, ignition, live fuels

NOMENCLATURE LISTING

A_s	surface area	Re	Reynolds number
Bi	Biot number	u	velocity (m/s)
c	specific heat	V	volume (m ³)
d	diameter (cm)	Greek	
D	characteristic dimension	ρ	density (kg/m ³)
h	heat transfer coefficient (W/m ² k)	ν	kinematic viscosity (m ² /s)
k	thermal conductivity	subscripts	
MC	moisture content	$conv$	convective
Nu	Nusselt number	dry	dry property
Pr	Prandtl number	i	initial
q''	heat flux (kW/m ²)	ig	at ignition
t	time (s)	$surf$	at surface
T	temperature (K)	∞	free stream value

INTRODUCTION

Wildland fires are an extremely costly problem. Crown fires, where live foliage ignites and burns, are particularly dangerous. Many wildland fire models assume radiation is the controlling heat transfer mechanism (such as [1, 2, 3, 4, and 5]). However, there is a growing indication that radiation is insufficient to ignite the small, thin fuel particles that carry a wildland fire. More and more evidence suggests that convective heating and flame bathing is a critical component (for example see [6] and [7]).

Unfortunately, ignition by convective heating of any fuel is relatively poorly understood as much of the ignition work in the literature has focused on ignition due to radiative heating. In one of the few works found that studied ignition due to pure convective heating, Niioka *et al.* [8] heated 20 mm diameter hemispheres of four different polymers (PMMA, PVC, HTPB, and CTPB) in a stagnation point flow. The flow velocity, oxygen fraction, and temperature were varied. It was demonstrated that two regimes exist – one controlled by the solid pyrolysis and the other by gas phase kinetics. In the pyrolysis controlled regime, increasing the flow velocity increases the heating rate of the fuel and thus decreases the ignition time. As the flow is further increased, however, the residence time becomes too small compared to the gas phase reaction time (large Damköhler number) and the solid ignition time begins to increase. This means that there is an optimal flow velocity that results in a minimum ignition time. A similar trend of ignition time but with Reynolds number was found by Wang and Yang in their experiments with PMMA [9]. Wang and Yang also noted that the surface temperature at ignition is strongly affected by the Reynolds number (see also [10]). The surface temperature at ignition may also be a function of the air temperature, as suggested by DiBlasi *et al.* [11]. Though these works have provided some important insights into convective ignition, their scope is still relatively limited. Further work to examine the effects of particle dimensions and shape, charring and glowing combustion, flow regime (stagnation vs. cross flow vs. parallel flow), flow temperature, and gas composition is still needed.

The study of ignition and subsequent flame spread of forest fuels has largely been performed using dried and dead fuels and only a few works were found that examined live fuels [12, 13, 14, 15, 16]. Dimitrakopoulos and Papaioannou [12], Jervis *et al.* [13], McAllister *et al.* [14], all studied ignition due to radiative heating. Xanthopoulos and Wakimoto [16] and Fletcher and coworkers ([15, 17, and 18]) were the only studies found that convectively heated live fuels to ignition. However, the study in [12] was primarily focused on developing an empirical correlation for the ignition time rather than investigating the physical processes involved in ignition. Fletcher and coworkers ([15, 17, and 18]) attempted to correlate the ignition time with leaf thickness and moisture content, however, almost no correlation with moisture content and only a slight correlation with leaf thickness were found. Though the heating mechanism was radiation, both Jervis *et al.* [13] and McAllister *et al.* [14] also noted a difference in the ignition behavior of live fuels than cannot be solely explained by moisture content. Jervis *et al.* [13] suggested that volatiles were lost in drying the fuels which contributed to the very different ignition behavior seen between live and dried. McAllister *et al.* [14] looked to the variation in the chemical composition of the live fuel to help explain the discrepancies. Dead forest fuels are primarily composed of cellulose, lignin, and hemicellulose and their dry weight remains constant. Live fuels, however, can be up to half non-structural carbohydrates like sugars and starches [14]. Because these non-structural carbohydrates are vital for the biological processes of the plant, the amount stored can vary during the growing season and thus the dry weight of the fuel can vary [19]. It is very possible that the apparent moisture content of the fuel can change solely due to changes in the dry weight while the relative amount of water stays constant (see for example [6] and [20]). A still unexplained empirical observation is the “moisture of extinction” [21]. Wildland fires in dead fuels will not spread above some threshold of fuel moisture content, typically assumed to be between 10 and 40% [21]. However, in crown fires, live fuels with moisture contents well above 70% are what carry the extremely vigorous fire. Clearly there is a complicated and unknown relation between the chemical composition and moisture content that has a significant effect on the ignition of live fuels.

This work is meant to be a first step towards understanding the complex behavior of the convective ignition of live forest fuels. Here we use hot air at two temperatures (500°C and 600°C) to ignite a wide range of forest fuels, both live and dead. The evolution of water from the fuels during heating and ignition is measured and discussed. The trends of the ignition time are discussed with the aid of simple heat transfer principles.

EXPERIMENT DESCRIPTION

The convective heating device consists of 2, 6.5-kW MHI¹ electric “airtorches” mounted horizontally and connected via a ceramic block manifold (see Fig. 1). The manifold combines the two airstreams and directs the flow through a gentle 90° bend so the outlet is vertically upward. The outlet port of the manifold is

¹ The use of trade names is provided for information purposes only and does not constitute endorsement by the U.S. Department of Agriculture.

15.24 cm (6 in) in diameter. The airflow rate through the airtorches is adjustable, however a minimum setting of 261 L/min per torch is recommended to prevent the torches from overheating. The airflow through the torches is controlled by two Omega FMA-2612A mass flow controllers, and is dried using a desiccant. The temperature of the airtorches is adjustable from ambient up to 1200°C. Controller units maintain the set point of each airtorch based on temperature measurements from K-type thermocouples located in the immediate outlet of each airtorch (prior to entering the manifold). Unfortunately, there are heat losses in the ceramic manifold, so the reported air temperature is measured using a K-type thermocouple located in the outlet of the manifold. The outlet of the manifold exhausts to the ambient air, and due to entrainment cools rapidly within a few centimeters above the outlet.

All fuels were tested at outlet air temperatures of 500°C and 600°C. For tests performed at 500°C, the total airflow rate was 546 L/min. In order to achieve 600°C at the outlet and to account for the reduced density, a slightly lower flow rate of 522 L/min was used. These flow rates correspond to an airflow velocity of 1.3 m/s at 500°C and 1.4 m/s at 600°C. A range of fuel samples were tested from dry wood sticks to live fuels from Florida, South Carolina, Southern California, Utah, and Montana. A full list of fuels tested is shown below in Table 1. The cast lodgepole pine needles were collected from the litter layer below the trees and only intact, non-degraded needles were considered (appearing light brown rather than dark grey). Each fuel and temperature combination was tested twice. The moisture content on a dry mass basis of each fuel was determined by either using a Computrac MAX 2000XL or weighing the fuel before and after drying in an oven at 100°C for a few days.

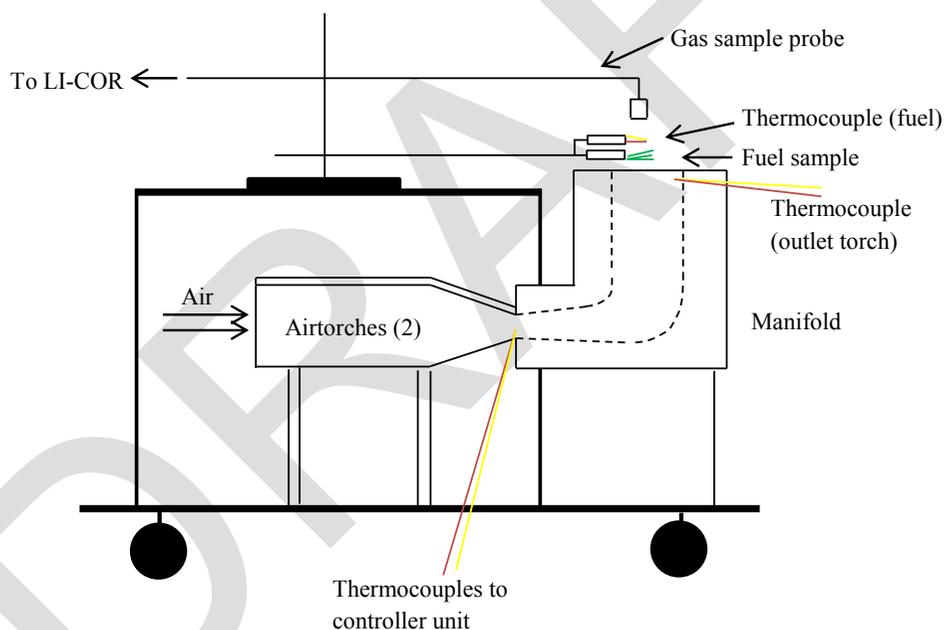


Fig. 1. Schematic of airtorch experiment.

Fuel samples were mounted using 0.6 cm diameter ceramic tubes that were 15 cm in length. Clean ceramic tubes were used for each test to avoid contamination. The ceramic tubes were cleaned by baking them overnight in a muffle furnace at 850°C. For each test, a ceramic tube with fuel sample was mounted onto a sliding mechanism that allowed the fuel to be quickly, easily, and reproducibly placed inside the hot air stream, right at the outlet of the manifold. A 5 mil (0.13 mm/0.005"/36 AWG) K-type thermocouple was mounted 2.2 cm directly above the fuel sample on the sliding mechanism (see Fig. 1). This temperature measurement helped to bracket the fuel temperature, synchronize the H₂O and CO₂ data with the ignition event, and to aid in the ignition time measurement. All ignition time measurements were made visually and confirmed with the thermocouple data.

Table 1 – Fuels tested and mounting procedure.

Sample description	Source	Dimensions	Mounting
Dry ponderosa pine (<i>P. ponderosa</i>) stick	California	1.59 mm (1/16") x 6 cm	Cotronics paper
Rehydrated ponderosa pine stick	California	1.59 mm (1/16") x 6 cm	Cotronics paper
Green Douglas-fir stem (<i>Pseudotsuga menziesii</i>)	Evaro, Montana	~1.9 mm x 2.5 cm stem	Cotronics paper
Dry cast lodgepole pine (<i>P. contorta</i>) (litter)	Evaro, Montana	~0.61 mm x 5 cm 4 needle clumps	Cotronics paper + binder clip
Rehydrated cast lodgepole pine (litter)	Evaro, Montana	~0.61 mm x 5 cm 4 needle clumps	Cotronics paper + binder clip
Dry live lodgepole pine	Evaro, Montana	~0.61 mm x 5 cm 4 needle clumps	Cotronics paper + binder clip
Rehydrated live lodgepole pine	Evaro, Montana	~0.61 mm x 5 cm 4 needle clumps	Cotronics paper + binder clip
Lodgepole pine	Evaro, Montana	~0.61 mm x 5 cm 4 needle clumps	Cotronics paper + binder clip
Douglas-fir	Evaro, Montana	~0.51 mm x 2.5 cm 4 needles	Cotronics paper + binder clip
Manzanita (<i>Arctostaphylos sp.</i>)	Riverside, California	~0.48 mm x ~2.5 cm x 5 cm, Leaf	Cotronics paper
Gallberry (<i>Ilex glabra</i>)	Apalachicola NF, Sophopy, Florida	~0.34 mm x ~1.5 cm x 5 cm, Leaf	Cotronics paper
Black titi (<i>Cyrilla racemiflora</i>)	Apalachicola NF, Sophopy, Florida	~0.25 mm x ~2 cm x 7 cm, Leaf	Cotronics paper
Chamise (<i>Adenostoma fasciculatum</i>)	Riverside, California	~6 mm x 4 cm branch tip	Cotronics paper
Sagebrush (<i>Artemisia tridentate</i>)	Provo, Utah	~15 mm x 4 cm branch tip	Cotronics paper
Wiregrass (<i>Aristida stricta</i>)	Coastal South Carolina	~0.4 mm x 6 cm 6 pieces	Cotronics paper + binder clip

Also listed in Table 1 is a description of how each fuel was mounted onto the ceramic tube. For the needles, four individual needles (Douglas-fir) or needle pairs (lodgepole pine) were held using a 2 cm binder clip lined inside and out with Cotronics paper. The binder clip was mounted into the ceramic tube via a 4 cm screw drilled through the wide part of the clip. Samples comprised of leaves and stems were mounted into the ceramic tube by wrapping the end of the fuel with a 0.5 cm strip of Cotronics paper to both insulate the fuel and hold it into place.

H₂O and CO₂ concentrations of the evolved products were measured using a LI-COR LI-7000 differential gas analyzer. One of the advantages of using a hot air stream as a source of convective heating is that it provides a relatively clean background for the LI-COR (as opposed to a gas burner). A stainless steel gas sampling probe was fixed in the hot airstream 6 cm above the fuel sample. The sampling probe had a 2.5 cm diameter, 3 cm long cylindrical collar to trap as much of the gasses released from the fuel sample as possible. The LI-COR and pump drew the gas sample through the probe at 2.5 L/min. The sample line

was wrapped in heat tape to maintain a line temperature of $\sim 100^{\circ}\text{C}$. This was monitored with a thermocouple placed directly on the steel tube, under the heat tape. The LI-COR analyzed the gas stream for H_2O and CO_2 at a rate of 10 Hz. The LI-COR data were logged using a Campbell Scientific CR3000, along with the temperature measurements made just above the fuel sample (“fuel temperature”), outlet of the manifold (“torch temperature”), and along the gas sample line (“probe temperature”).

SIMPLE HEAT TRANSFER ANALYSIS

Because most, if not all, of the thermal properties of live forest fuels are completely unknown, a complete heat transfer and ignition model cannot be performed at this time. Instead, some of the relevant heat transfer relations will be suggested as to their possible role in explaining the experimental results. A quick summary is provided here.

All of the fuels tested have very different shapes and sizes, thus the Nusselt numbers and convective heat transfer coefficients will vary from fuel to fuel. There are three categories of fuels tested: leaves, needles, and sticks. In order to simplify the discussion as much as possible (and because there simply aren't any more appropriate relations), the leaves will be treated as a flat plate in a cross flow and both the needles and sticks as circular cylinders in a cross flow. For the needles and sticks, the average Nusselt number over a very wide range of Reynolds numbers is given by the Churchill and Bernstein relation [22]

$$\overline{Nu}_D = 0.3 + \frac{0.62 \text{Re}_D^{1/2} \text{Pr}^{1/3}}{\left[1 + (0.4/\text{Pr})^{2/3}\right]^{1/4}} \quad (1)$$

where the Reynolds number for a characteristic diameter is

$$\text{Re}_D = \frac{u_{\infty} D}{\nu}$$

Because the temperature of the air is so high, the kinematic viscosity is also high ($80.31 \times 10^{-6} \text{m}^2/\text{s}$ at 500°C to $97.99 \times 10^{-6} \text{m}^2/\text{s}$ at 600°C). Combined with the small diameters of these fuels, the Reynolds numbers tend to be quite low (see Table 2). Unfortunately, no Nusselt number correlation was found in the literature for a flat plate in cross flow that is valid for this range of Reynolds numbers. Because this analysis is purely meant to be qualitative, our discussion will make use of the relation derived by Hilpert [23,24] (with the correct values of the constants from [25])

$$\overline{Nu}_D = 0.231 \text{Re}_D^{0.731} \quad (2)$$

while keeping in mind that this correlation is valid only for Reynolds numbers in the range of 6×10^3 to 2.4×10^4 . Table 2 lists some approximate values of the Reynolds number, Nusselt number, and convective heat transfer coefficient (h) for each fuel tested. It is important to remember that the heating rate of the fuel is not uniform over the fuel surface. The heat transfer coefficients and calculated heat fluxes are average values and that, due to the nature of the flow around the fuel particles, there will be regions that experience both significantly higher and lower values (for example at the stagnation point versus the lee side). Additionally, average fuel diameters and thicknesses were used, so there will also be some variability along the length of the fuel due to tapering and widening of the fuel along its length.

Another important piece of the puzzle is the fuel temperature in response to the convective heating. The two extreme models of transient heat conduction are the lumped capacitance model (thermally thin) and the semi-infinite solid model (thermally thick). For simplicity, the time to reach an assumed ignition temperature (T_{ig}) for both of these models will assume only convective heating with a constant convective heat transfer coefficient and constant material properties. From [24] for example, for the lumped capacitance model, the ignition time is given by

$$t_{ig} = \frac{\rho V c}{h A_s} \ln \left(\frac{T_i - T_\infty}{T_{ig} - T_\infty} \right) \quad (3)$$

and for the semi-infinite solid (where only the surface reaches the ignition temperature), the ignition time can be found from

$$\frac{T_{ig,surf} - T_i}{T_\infty - T_i} = 1 - \exp \left(-\frac{h^2 \alpha t_{ig}}{k^2} \right) \operatorname{erfc} \left(1 + \frac{h \sqrt{\alpha t_{ig}}}{k} \right) \quad (4)$$

Table 2a. Convective heat transfer approximations for air temperature of 500°C. LP = lodgepole pine.

	Char. D (cm)	Re	Nu	h (W/m ² K)	q ^{''} _{conv} (kW/m ²)	Thick- ness (mm)	Bi (k _{wood})	Bi (k _{water})
Dry p. pine stick	0.159	25.7	3.60	97.4	45.8	1.59	1.55	NA
Rehydrated p. pine stick	0.159	25.7	3.60	97.4	45.8	1.59	1.41	NA
Green Doug-fir stems	0.19	30.8	3.91	88.5	41.6	1.9	1.53	0.25
Dry cast LP	0.061	9.9	2.34	165.1	77.6	0.61	0.92	NA
Rehydrated cast LP	0.061	9.9	2.34	165.1	77.6	0.61	0.92	0.15
Dry live LP	0.061	9.9	2.34	165.1	77.6	0.61	0.92	NA
Rehydrated live LP	0.061	9.9	2.34	165.1	77.6	0.61	0.92	0.15
Lodgepole pine	0.061	9.9	2.34	165.1	77.6	0.61	0.92	0.15
Douglas-fir	0.051	8.3	2.17	182.7	85.9	0.51	0.85	0.14
Manzanita	4	648	40.93	44.0	20.7	0.48	0.19	0.03
Gallberry	4.5	728	44.61	42.6	20.0	0.34	0.13	0.02
Black Titi	7	1133	61.62	37.9	17.8	0.25	0.09	0.01
Chamise	0.6	97	6.74	48.3	22.7	0.74	0.33	0.05
Sagebrush	1.5	243	10.55	30.2	14.2	0.28	0.08	0.01
Wiregrass	0.04	6.5	1.95	209.9	98.7	0.04	0.08	NA

The heat losses from reradiation have been ignored in the above equations. If an ignition temperature of 350°C and emissivity of 0.7 are assumed, the reradiation heat flux is at most about 5.5 kW/m². The Biot number (Bi = hL/k) is often used to determine the appropriateness of the above models. Table 2 shows the possible range of Biot numbers for the fuels tested. Because the thermal conductivity is unknown, the Biot number is calculated using both the thermal conductivity of dry wood (0.10 W/mK [26]) and of pure water at 100°C (0.68 W/mK). The leaf thickness is used here for the characteristic length of both the leaves and the chamise and sagebrush branch tips.

To include the effect of the moisture content on the ignition time, Babrauskas [10] suggests merely adding a term to the dry ignition time that accounts for the time it takes to partially dry the material:

$$t_{ig} = t_{ig,dry} + \frac{a d \rho_{dry} MC}{\alpha_s \dot{q}_e''} \quad (5)$$

where $a = 33,200(\dot{q}_e'')^{-2} - 8.7$. While this relation was developed for radiant heating of dead fuels, it is mentioned as a discussion point.

Table 2b. Convective heat transfer approximations for air temperature of 600°C. LP = lodgepole pine.

	Char. D (cm)	Re	Nu	h (W/m ² K)	q ^{''} _{conv} (kW/m ²)	Thick- ness (mm)	Bi (k _{wood})	Bi (k _{water})
Dry p. pine stick	0.159	22.7	3.48	100.9	57.5	1.59	1.60	NA
Rehydrated p. pine stick	0.159	22.7	3.48	100.9	57.5	1.59	1.46	NA
Green Doug-fir stems	0.19	27.1	3.78	91.6	52.2	1.9	1.58	0.26
Dry cast LP	0.061	8.7	2.27	171.2	97.6	0.61	0.95	NA
Rehydrated cast LP	0.061	8.7	2.27	171.2	97.6	0.61	0.95	0.15
Dry live LP	0.061	8.7	2.27	171.2	97.6	0.61	0.95	NA
Rehydrated live LP	0.061	8.7	2.27	171.2	97.6	0.61	0.95	0.15
Lodgepole pine	0.061	8.7	2.27	171.2	97.6	0.61	0.95	0.15
Douglas-fir	0.051	7.3	2.10	189.6	108.0	0.51	0.88	0.14
Manzanita	4	572	38.74	41.7	23.7	0.48	0.18	0.03
Gallberry	4.5	643	42.22	40.4	23.0	0.34	0.12	0.02
Black Titi	7	1000	58.32	35.8	20.4	0.25	0.08	0.01
Chamise	0.6	85.7	6.51	46.6	26.6	0.74	0.31	0.05
Sagebrush	1.5	214	10.17	29.2	16.6	0.28	0.07	0.01
Wiregrass	0.04	5.7	1.89	203.5	116.0	0.04	0.07	NA

The thermal properties of the fuels will clearly have a large role in the ignition time. As previously stated, however, they are entirely unknown for live forest fuels. While there are some values available in the literature for oven dried fuels, the variation of these properties with moisture content is unknown. There are relations available for the variation in specific heat, density, and thermal conductivity of wood [26]. These relations were used to calculate the Biot number for the rehydrated wood sticks in Table 2.

$$\rho = \rho_{dry}(1 + MC/100)$$

$$k = (\rho_{dry} / \rho_{water}) (0.1941 + 0.004064MC) + 0.01864$$

$$c = \frac{(c_{dry} + c_{water}MC/100)}{(1 + MC/100)} + MC(-0.06191 + 2.36 \times 10^{-4}T - 1.33 \times 10^{-4}MC)$$

where T is in Kelvin. These must be taken very cautiously, as they are valid only for dead wood with very different internal structure, and for the specific heat and conductivity, only up to the fiber saturation point (i.e. MC ≤ 25% (live fuels can have MCs well over 100%)).

RESULTS AND DISCUSSION

Before the quantitative results are discussed, there are some visual observations made during the tests that are worth noting. Almost all of the live fuels made audible popping and crackling noises while heating, but none of the dry or rehydrated fuels did. The only live fuel that did not make these noises while heating was the sagebrush. This behavior has been noted by others [15,17,18] and it is speculated that the noises are due to the sudden bursting of cell walls and expulsion of water. Unlike dead fuels, live fuels can store large amounts of water within the cells themselves which are like balloons that can expand up to a certain point. Once the pressure inside the cell is too great, the walls burst. In fact, all of the leafy fuels tested developed large blisters on the surface (see Fig. 2). Sagebrush was the only live species tested that didn't have a distinctive waxy coating on the outside of the leaves. It's possible that the cell walls of the sagebrush are much more permeable so that the pressure inside the cells doesn't build during heating. The moisture release would then be more of a diffusive process than an explosive one. A similar trend was noted by others ([15,17,18]) and when heating green grasses in some early scoping tests.



Fig. 2. Bubbles and blisters on live fuels. Left and Center: Gallberry. Right: Manzanita.

Another intriguing visual observation was that most of the live fuels had tiny bright sparks downstream immediately after initiating the heating. The manzanita leaves also released visible white puffs of gas before ignition. These sparks and flashes tended to correspond to the audible popping noises. It is possible that more than just water is released during these explosive events, such as cell contents (sugars and starches) and cell walls.

Many of the live fuels and the thicker dry wood sticks experienced localized glowing combustion before flaming ignition occurred. This glowing often occurred at the tips of the fuel where it is the thinnest. The glowing then served as a pilot for the flaming ignition.

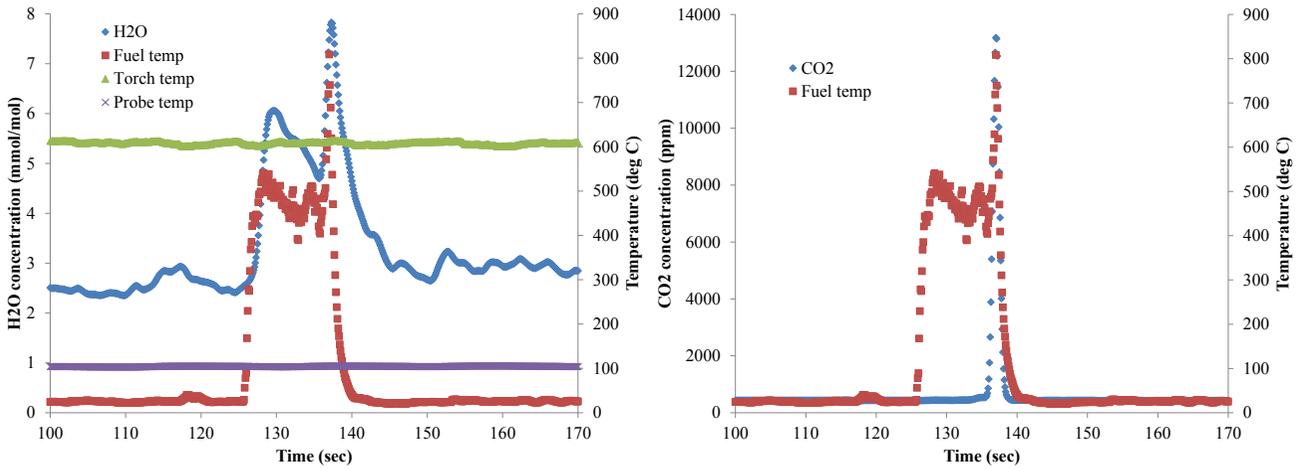


Fig. 3. Evolved H₂O and CO₂ from lodgepole pine needles at 600°C.

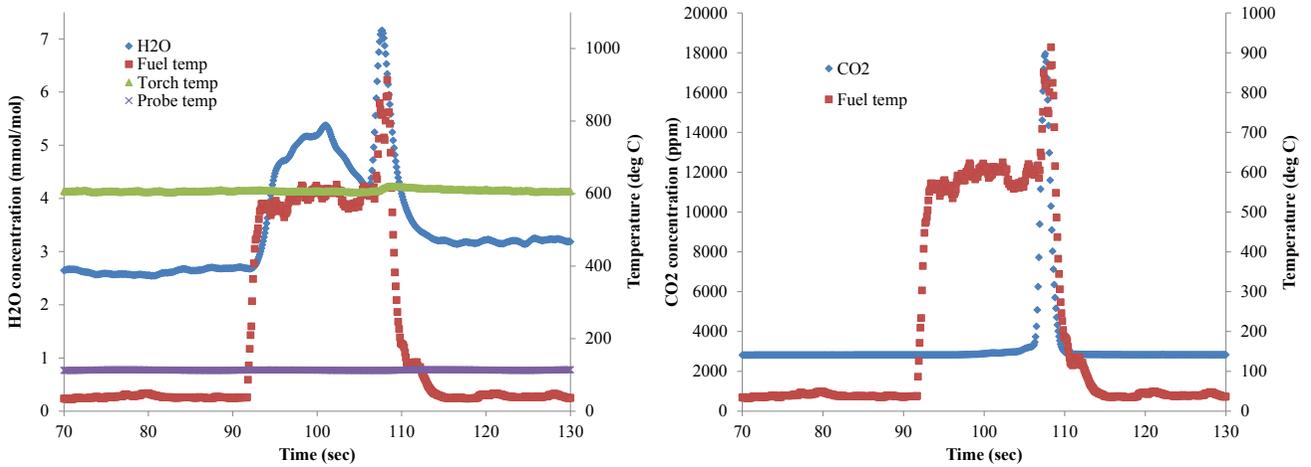


Fig. 4. Evolved H₂O and CO₂ from a manzanita leaf at 600°C.

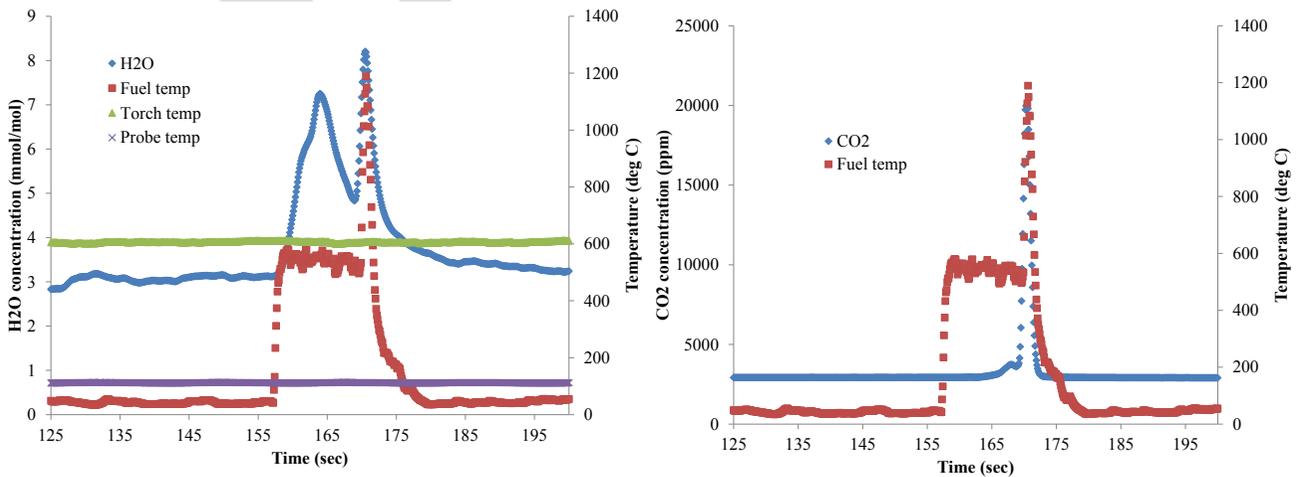


Fig. 5. Evolved H₂O and CO₂ from a gallberry leaf at 600°C.

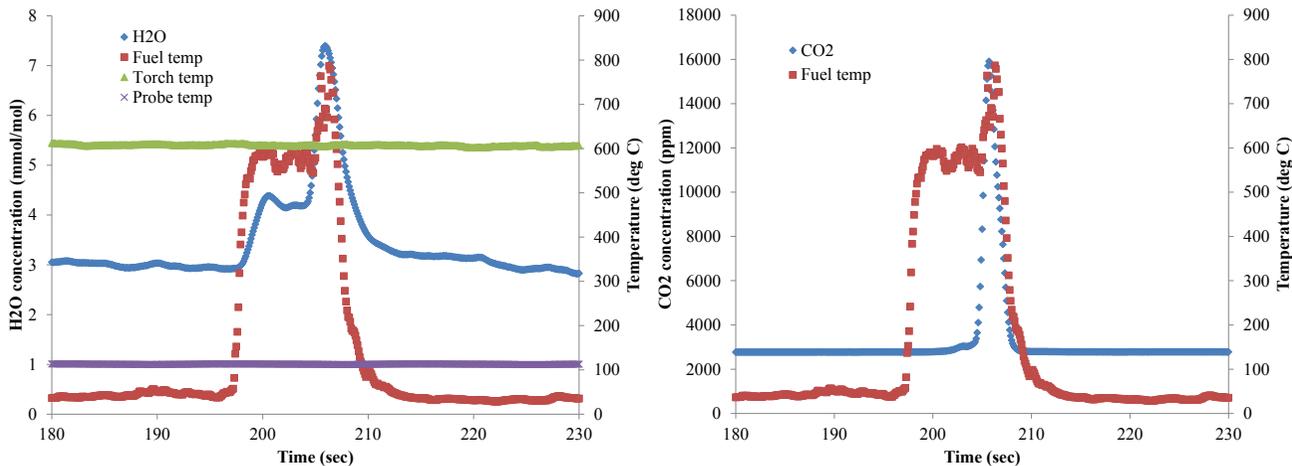


Fig. 6. Evolved H₂O and CO₂ from a chamise branch tip at 600°C.

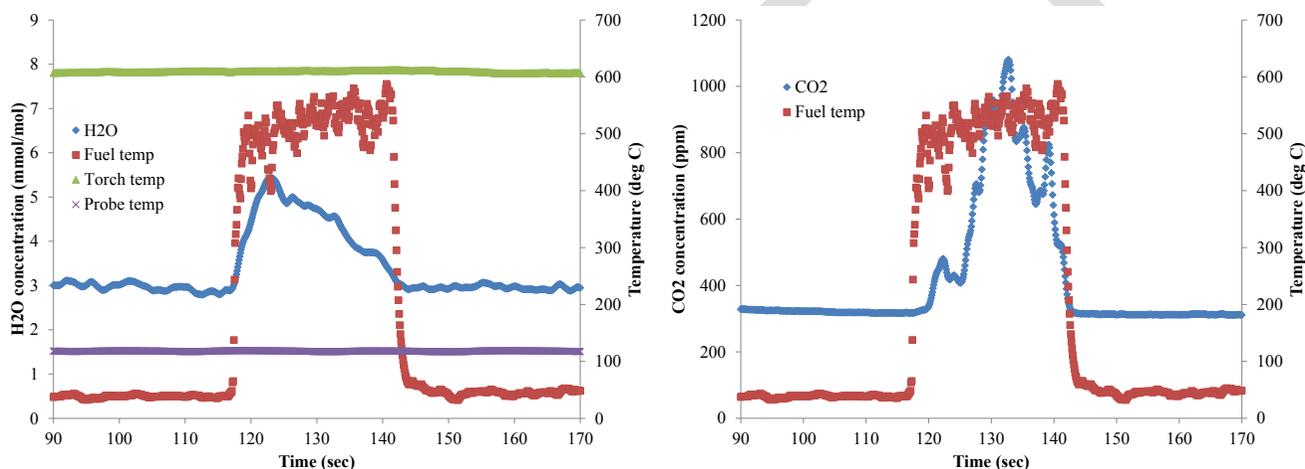


Fig. 7. Evolved H₂O and CO₂ from a sagebrush branch tip at 600°C (no ignition).

To gain some insight into how and when water is driven off relative to ignition, the H₂O and CO₂ concentrations were measured. Figs. 3-7 show the typical trends seen for lodgepole pine needles, manzanita leaves, gallberry leaves, chamise branch tips, and sagebrush branch tips at 600°C. The H₂O and CO₂ measurements were time shifted to account for the lag due to the long sample tube length (about 3 seconds). Also shown in these plots are the air temperatures measured just above the fuel (“fuel temperature”) and at the outlet of the torch (“torch temperature”) along with the temperature of the gas sampling probe (“probe temperature”). It is important to remember that, despite its name, the fuel temperature is not the actual fuel temperature, but the temperature of the air above. In all cases, the water concentration sharply increases when the fuel is first heated, and then begins to slowly decrease until ignition. At ignition, a sharp increase in the water and carbon dioxide concentrations occurs that coincides with the sharp increase in “fuel” temperature.

From Figs. 3-7, it is clear that all live fuels are still evolving water at the time of ignition. This is particularly noticeable with the chamise branch tips where the concentration of water in the products stays relatively constant just prior to ignition. In all fuels tested, it is possible that the sharp increase in water concentration at ignition includes both water due to combustion but also the remaining free water in the fuel. Even though the Biot numbers in Table 2 indicate that many of these fuels, including the chamise, nearly satisfy the criteria for the lumped capacitance model, the continuing release of moisture indicates

that there are still large temperature gradients within even the thinnest fuels. Figure 7 shows the no ignition case of sagebrush. Notice that there is only one peak in the water concentration as the fuel is first heated, and no subsequent second peak and no corresponding peak in the “fuel” temperature and CO₂ concentration that would indicate flaming ignition. Though the concentrations are much lower, CO₂ is still produced during heating, indicating the presence of glowing combustion.

Average moisture contents and ignition times for torch temperatures of both 500°C and 600°C are shown below in Table 3.

Table 3. Moisture content and ignition times. NI = no ignition, NT = not tested, and LP = lodgepole pine.

	500°C				600°C		
	MC (%)	t _{ig} (s) - #1	t _{ig} (s) - #2	t _{ig} (s) - ave	t _{ig} (s) - #1	t _{ig} (s) - #2	t _{ig} (s) - ave
Dry p. pine stick	0	19.8	17.9	18.85	7.5	5.8	6.65
Rehydrated p. pine stick	6	28.7	16.7	22.70	5.4	6.9	6.15
Green Doug-fir stems	83.0	char	char	NI	25.3	28.8	27.05
Dry cast LP	0	5.7	5.4	5.55	2.6	1.3	1.95
Rehydrated cast LP	8	8.7	7.6	8.15	1.6	2.7	2.15
Dry live LP	0	glowing	6.7	6.70	1.4	3.5	2.45
Rehydrated live LP	9	15.5	glowing	15.50	3.7	2.2	2.95
Lodgepole pine	133.9	16.9	12.7	14.80	11.2	10.2	10.70
Douglas-fir	143.1	glowing	glowing	NI	glowing	11.9	11.90
Manzanita	97.0	glowing	glowing	NI	14.6	10.8	12.70
Gallberry	129.0	char	char	NI	10.5	12.8	11.65
Black Titi	141.0	glowing	glowing	NI	10.3	7.5	8.90
Chamise	58.6	51.1	34.6	42.85	8.8	7.2	8.00
Sagebrush	107.3	glowing	glowing	NI	20.2	glowing	20.20
Wiregrass	5.1	1.3	1.7	1.50	NT	NT	NT

The dry and rehydrated pine wood sticks ignited at both temperatures tested. At 500°C, the rehydrated sticks with the 6% moisture content had a longer ignition time compared to the dry sticks as expected from Eq. 5 above. However, that trend is reversed at 600°C and the rehydrated stick actually ignited slightly faster than the dry stick. The “green” Douglas-fir stems had a much higher moisture content (higher than the fiber saturation point of dead wood) and did not ignite at all at 500°C. At 600°C, the stems took over three times longer than the ponderosa pine sticks to ignite. In addition to the large increase in moisture content between the dry sticks and the green stems, there are some geometric differences that influence the heat transfer and subsequent temperature rise. As seen in Table 2, the difference in fuel diameter results in a difference in the convective transfer coefficient of about 10%. As indicated in the Biot numbers, the dry sticks are more of a thermally intermediate solid, but because of the high moisture content and resulting high thermal conductivity, the stems could be more closely considered a thermally thin solid which will affect the way in which the solid heats up.

In comparing the ignition time of the dried “live” lodgepole needles to the dried cast needles, there is a very slight difference in ignition times. This could be natural variability in the experiment, but could also be due to the difference in needle composition between cast and live needles. As discussed earlier, non-structural

carbohydrates (such as sugars and starches) can constitute up to 50% of live needle mass [14]. Normally, the tree removes these valuable carbohydrates so that the cast needles are primarily structural carbohydrates (cellulose, hemicellulose, and lignin). The dried live needles would have retained these carbohydrates. Another interesting observation is that one sample of the dried live needles didn't have a flaming ignition at 500°C but showed glowing combustion. This suggests that the composition of the needles can vary from needle to needle. Because only four needle clumps were burned at a time, variations of the needle chemistry may have an influence on the ignition behavior.

The difference between the live and cast needles was much more apparent when rehydrated to 8-9%. Even though both live and cast needles were dried completely then rehydrated at the same temperature and relative humidity (35°C and 65% RH), the resulting moisture content was slightly different due to hysteresis effects and the presence of waxy coatings [27]. Though the difference in moisture content was only 1%, the ignition behavior at 500°C was markedly different. The cast needles readily ignited whereas the live needles took twice as long or didn't ignite at all. As discussed above, this suggests that the difference in chemical composition of the live versus dead needles can be influencing the ignition.

Interestingly, the only live fuels that ignited at 500°C were the lodgepole pine needles and the chamise branch tips. All other live fuels exhibited glowing combustion until the entire fuel sample was consumed, or in the case of the gallberry leaf, merely charred. The live lodgepole needles even ignited as fast or faster than the rehydrated needles with substantially lower moisture contents (9% MC). At 600°C, all of the live fuels ignited. The decrease in ignition time as the temperature was increased was much more pronounced with the rehydrated live needles than with the fresh live needles. The rehydrated live needles ignited 5 times faster while the fresh live needles only ignited about 1.3 times faster. Clearly there are significant differences in the thermal properties of fresh and rehydrated fuels and also the way the live fuels store water.

At 600°C, the needles ignited much faster than the leaves. As shown in Table 2, the needles have a much higher convective heating rate than the leaves so this is no surprise. What is surprising is the leaf ignition time trend. Manzanita had the highest heat transfer coefficient and the lowest moisture content of the leaves, and yet had the longest ignition time. Conversely, black titi had the lowest heat transfer coefficient and high moisture content, yet had the shortest ignition time. As shown in Table 2, all leaves are thin enough to more closely follow the lumped capacitance model which implies that the ignition time is proportional to the leaf thickness (Eq. 3). The Black titi leaves were about half as thick as the manzanita leaves which helps explain how a leaf with such high moisture content can ignite more quickly.

Because the sagebrush branch tips were full and dense, the characteristic diameter when calculating the Reynolds and Nusselt numbers is much larger than the other cylindrical fuels. This means that the heat transfer coefficient and thus the convective heating rate is much lower, contributing to a long ignition time. However, the chamise also had a similar low convective heating rate with much thicker leaves but ignited just as quickly as the single leaf fuels. This could be due to the low moisture content, but again, there could be some chemical composition differences (including the presence of or absence of a waxy leaf coating) between these fuels effecting the ignition time.

The wiregrass ignited almost instantaneously in 500°C. This was a very thin fuel with a very high convective heat transfer coefficient and heating rate. Because it ignited so quickly at 500°C, it was not tested in 600°C.

CONCLUSIONS

Work on live fuel ignition processes is just beginning, but has already shown a number of responses that conflict with standard concepts of wildland fire behavior and which must be crucial to understanding fire spread in live vegetation canopies. First, water is present in most live fuels after ignition. This means that steep temperature gradients exist in fuel particles and that water vapor must be accounted for in live fuel combustion after ignition. Second, this also means that live particles are probably poorly approximated as thermally thin elements. Third, geometric properties of the live leaves (thickness, aspect ratios of surfaces) vary among species to the degree that they affect ignition independently of thermal characteristics. Finally, this work points out the gap in basic knowledge of convective heat transfer within the low range of Reynolds number common to flame impingement on live vegetation.

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