

Experimental study on the burning behaviour of *Pinus halepensis* needles using small-scale fire calorimetry of live, aged and dead samples

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SUMMARY

Limited research has been conducted on the burning characteristics of live fuels, which are commonly assumed to behave like moist dead fuels. We use small-scale laboratory calorimetric experiments to investigate the differences in fire dynamics between live and dead *Pinus halepensis* needles. The study includes laboratory-aged samples and different moisture conditions (fresh or oven dry). A series of ten fire behaviour parameters are extracted from the measurements to identify and quantify differences. The main parameters are the following: time to ignition; flaming time; mass loss pre-ignition, during flaming, and during smouldering; peak power; effective heat of combustion; mean and peak CO/CO₂; and radiative fraction. Using these parameters, we show that the most flammable samples are fresh dead and aged needles, followed by dry dead and dry live needles. The least flammable is fresh live needles. Live needles ignite about four times slower, and burn with ~60% lower power and ~50% lower heat of combustion than dead needles. Aged needles resemble most closely the behaviour of dead needles, but many fire behaviour parameters were significantly different. The results confirm the importance of moisture content in the burning behaviour of pine needles, but the differences between live and dead samples cannot be explained solely in terms of moisture but require consideration of plant chemistry and sample drying. © 2015 The Authors. Fire and Materials published by John Wiley & Sons, Ltd.

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1. INTRODUCTION

The high flammability of conifer forests in the Mediterranean and Boreal biomes is due mostly to the presence of needles in very large amounts. Needles are fine fuels that ignite and spread flames faster than coarse woody fuels [1, 2] and represent an important portion of the total fuel consumption in wildfires. Needles are found both in the tree canopies and on the ground. Live needles (green colour) are part of the foliage and typically burn in crown fires. Dead pine needles (red colour) are on the ground, accumulating gradually on the litter and humus layers, and burn both in surface and ground fires. Dead needles on the ground are also prone to ember ignition, which is of importance in wildland and at wildland–urban interface [3]. The presence of live needles on the ground and dead needles on the foliage does occur but is of lower importance to fire behaviour because these

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conditions are short lived and occur in smaller quantities. A notable exception is the case of a conifer stand attacked by bark beetle, because it can lead to substantial amounts of dead needles in the tree crowns [4] thus significantly affecting wildfire behaviour.

A common assumption in wildfire science has been to understand live fuels simply as very moist dead fuels [5, 6]. This assumes that moisture content (MC) dominates ignition and flame spread and neglects any fuel structure or chemical composition difference between live and dead fuels. Finney *et al.* [6] describe that the assumption stemmed from early fire experiments conducted solely on dead fuels for which results were then extrapolated to live fuels.

A review of the literature shows that the origin of the assumption that live fuels behave like moist dead fuels can be traced back to the 1960s (Pickett *et al.* [7]) and, it was based on two experimental findings. The first finding is that MC is the single most important fuel factor affecting wildfire behaviour [2, 8, 9]. The other three factors of importance are structure (surface-area-to-volume ratio, bulk density and porosity), chemical composition (content in plant tissues of lignin, carbohydrates and minerals) and fuel arrangement. The second finding is that the range of MC naturally occurring in each of these two fuel types is very different. While the MC of live fuels ranges from 30% to 300% on a dry weight base, in dead fuels, it ranges from 2% to 40% [8–10]. These two findings are correct but not complete, and the limited research conducted on the burning characteristics of live fuels has not allowed for a correction of this assumption. Pickett *et al.* [7] pointed out that this simplification has contributed to the poor predictive skills of many wildfire models for live fuels, because they represent conditions away from the dead fuel's data used in model calibration.

This paper reports laboratory results on the burning of live, aged and dead (both fresh and dried) *Pinus halepensis* needles. This species was chosen as a common and representative Mediterranean fuel of interest to wildfire studies, which freshly collected samples were available to the authors as part of the EU project *Fire Paradox*. The results aim to contribute towards the understanding of the flammability changes from live to dead in fine fuels.

We tested samples in the Fire Propagation Apparatus (FPA) [11] using a porous sample holder. The FPA is the most advanced fire calorimetry technique to date. Fire calorimetry was chosen because it is the state of the art of experimental fire science [11, 12]. It measures the power from small samples, and the burning conditions can be controlled and varied to provide a fundamental framework of study. Among the first wildland calorimetry studies are White *et al.* [13], Weise *et al.* [8] and Dibble *et al.* [14] who used the cone calorimeter. Studies by Schemel *et al.* [15], Bartoli *et al.* [16] and Simeoni *et al.* [17] conducted tests in the FPA on a range of pine needle species in dry conditions. Over the cone calorimeter, the FPA offers the additional advantage of excellent control of the flow field around and across the sample (Figure 1), which is important for natural fuels [15]. The use of advanced calorimetry, in addition, allows us to measure fire in the literature parameters not reported before for wildfire fuels, like the radiative fraction and CO/CO₂ ratio.

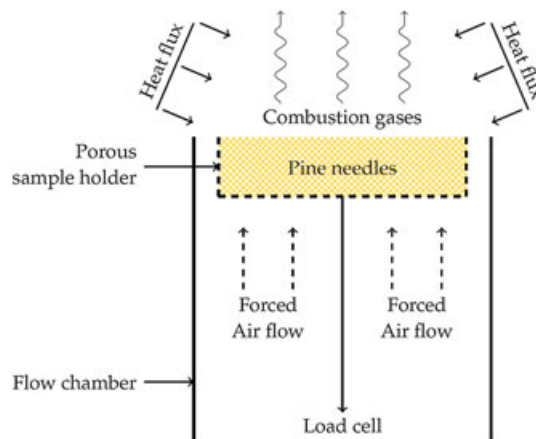


Figure 1. Schematic of the heat and flow conditions around a sample of needles in the porous holder inside the Fire Propagation Apparatus. For reference, the holder is 130 mm in diameter and 30 mm deep. (Figure by R Hadden, CC-BY license).



Figure 2. Samples of *Pinus halepensis* needles used in the experiments (from left to right): live, aged and dead.

2. MATERIALS AND METHODS

2.1. Experimental protocol and devices

The experimental procedures were carried out in accordance to ASTM E2058-03 [18]. As shown in Figure 1, the top surface of the sample is exposed to a uniform radiant heat flux large enough to ignite the fuel and establish a flame. The heat flux is produced by infrared heaters set at 50 kW/m^2 for these experiments. The spectral radiation of these heaters is below the $5\text{ }\mu\text{m}$ wavelength [19] and includes the upper wavelength range of radiation from vegetation flames [20]. The porous sample holder is a circular basket open at the top and is made of stainless steel mesh measuring $130\pm 1\text{ mm}$ in diameter and $30\pm 0.5\text{ mm}$ in depth. It was developed originally by Schemel *et al.* [15], where it was shown that the flow inside wildland fuel beds has a significant impact on the combustion dynamics. The standard sample holder is non-permeable to flow (it is made of solid metallic sheets instead of mesh) and thus leads to unrepresentative flow conditions in natural fuel beds. The porous holder opening is 63%, which is the highest value that did not allow needles to be lost through the openings. Experiments are conducted under both natural and forced flow conditions. When the forced convection is active, the volumetric flow is 200 l/min , which provides an upstream velocity at the sample centerline of $0.46\pm 0.02\text{ m/s}$, as measured before the tests with a hot wire anemometer under no heat-flux. The downstream airflow velocity at the sample centerline is between $0.12\pm 0.01\text{ m/s}$ for the initial full sample, and $0.22\pm 0.02\text{ m/s}$ for the empty holder (when the sample has been consumed). The monotonic increase of the airflow after ignition is an intrinsic part of the experimental setup, also present in any laboratory study of porous fuel beds, even those conducted under natural convection (albeit resulting in a lower velocity increase). Each experiment was repeated at least four times, and for some cases up to six times, in order to obtain the full range of experimental uncertainties and statistically valid data.

2.2. Sample preparation

Examples of the fuel types investigated are shown in Figure 2. Live needles of *P. halepensis* were collected by hand from arbitrary locations in the crowns of different trees during the spring[‡] of 2008 in the Mediterranean coast of France near Avignon. At the time of testing, live samples had a wet-base MC[§] of $48\pm 4\%$ (92% in dry base). These samples were shipped in sealed containers and tested within 1 week after collection. Dead needles were collected from the forest litter at the same locations and time as the live needles. They were tested within 5 weeks of collection and in the meantime were maintained inside a climatic chamber, away from direct sunlight, and at standard conditions ($25\text{ }^\circ\text{C}$ and 50% air humidity). At the time of testing, the measured MC of the dead needles was $7.5\pm 1\%$. Note that the MC of needles varies widely with the weather conditions and

[‡]There was no particular reason for the selection of the Spring time for collection. For the effect of seasonality in burning behaviour of samples, see McAllister *et al.* [21].

[§]Samples were oven dry at $60\text{ }^\circ\text{C}$ during 48 h for measurements of moisture content (MC). Unless otherwise stated, MC values are given in wet base

the seasons, as previously stated. The ignition work of Weise *et al.* [8] and McAllister *et al.* [21] shows that the effect of seasonal variations is important. But testing over the whole range of possible MC values is out of the scope of the present work. Instead, we have focused on the two most interesting MC values, fresh and oven-dry conditions. Subsets of the live and dead needles were dried in the oven at 60 °C for 48 h. The measured MC was $2 \pm 1\%$ for both. Note that MC for oven-dry samples is not zero, first because of measurement errors ($\pm 1\%$) and also because the samples quickly reach equilibrium with ambient humidity in the laboratory and gain a small amount of moisture once out of the oven, while preparing the tests [22]. An additional sample series was created to test the effect of aging from a subset of fresh live needles stored at near standard conditions (18 ± 5 °C and $40 \pm 10\%$ air humidity) for a period of 15 months after collection. These are referred to as aged samples. At the time of testing, the measured MC was $7.5 \pm 1\%$.

Samples of needles were prepared with a fixed mass of 8 g (Figure 2), which provides a bulk density of 20 kg/m^3 inside the FPA holder. This is similar density to that encountered in the litter of some Mediterranean forests [23]. This density is however, much higher than the bulk densities measured in the crowns of pine trees, which has been determined to be around 0.2 kg/m^3 [24]. The effect of the sample mass and density on the results could be significant as reported by Bartoli [25] and Jervis [26].

2.3. Measurements of fire behaviour

A series of 80 experiments were conducted for piloted ignition. The direct measurements obtained from the FPA are the power (heat release rate, HRR), the transient mass of the sample, and the carbon monoxide (CO) and carbon dioxide (CO₂) concentrations in the smoke. From these data, we extract a series of fire parameters. The main ones are time to ignition, flaming time, mass loss pre-ignition, mass loss during flaming, mass loss during smouldering, peak power, effective heat of combustion, CO/CO₂ and radiative fraction. The HRR is measured through CO and CO₂ generation calorimetry (chemical HRR). We also measure the convective HRR using the gas temperature rise in the exhaust duct [11]. The mass flux is obtained by deriving mass over time and smoothing the signal with the supsmooth algorithm. The effective heat of combustion is calculated by integrating the chemical HRR over time and then dividing by the initial mass. Note that we report the effective heat of combustion from fire calorimetry. The heat of combustion most reported in the literature is that measured by a bomb calorimeter, which is the maximum value released in ideal combustion conditions (e.g., engines), often far from those encountered in wildfires [27]. The radiative fraction of the HRR is obtained from the difference between the chemical and convective HRR measurements (divided by the chemical HRR).

A description and justification of the different parameters of interest to wildfires that can be obtained from analysis of calorimetry data is found in Drysdale [29] and Byram [30]. For example, the flame spread rate is inversely proportional to the time to ignition [29]. The depth of the fire front is proportional to the flaming time (and the bulk density), and the fire intensity per unit length of fire front is proportional to the HRR and the depth of the front [30]. The CO/CO₂ ratio is typically around 0.1 for flaming fires and serves to quantify the combustion efficiency; larger ratio indicates poorer combustion (perfect combustion would yield a 0 ratio). The radiative fraction [29] serves to quantify fundamental differences in the physics and chemistry of the flame. White and Zipperer [28] also offer an in-depth discussion of the advantages and disadvantages of small-scale and laboratory tests, including calorimetry, in the understating of wildfires. The advantages and the difficulties of up-scaling fire results from the laboratory to the field are reviewed by Torero and Simeoni [31] and Perez *et al.* [32].

3. RESULTS

3.1. Transient measurements

Figure 3 shows the measurements of mass loss and HRR for three fuels under natural flow. At the time of ignition, the HRR increases as the flame spreads across the sample, reaches a peak value and then

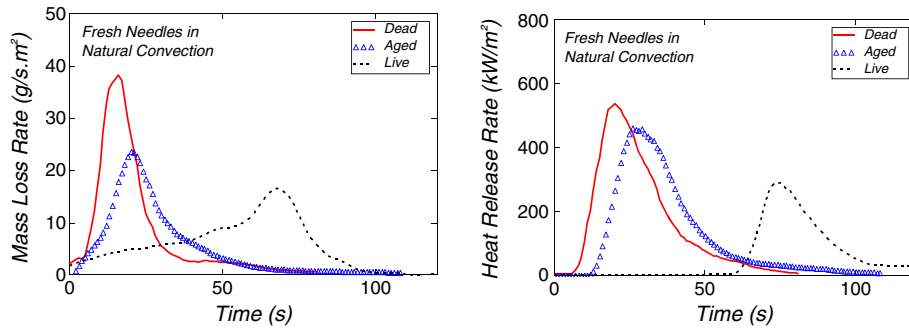


Figure 3. (Left) Mass loss rate and (Right) heat release rate for fresh needles under natural convection.

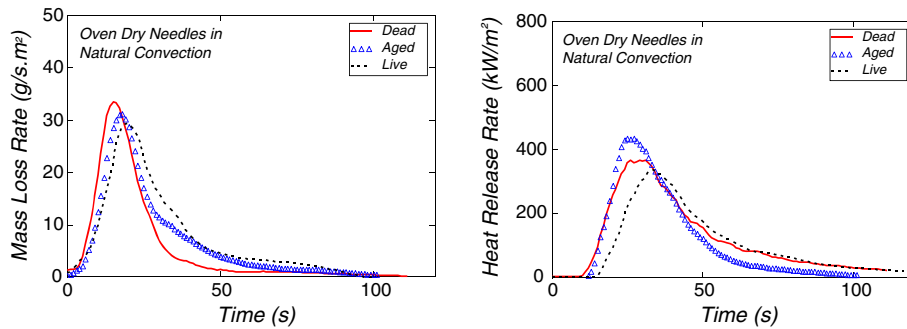


Figure 4. (Left) Mass loss rate and (Right) heat release rate for dry needles under natural convection.

decays as the sample is consumed. Pre-ignition mass loss is between 45% and 55%[¶] for live needles and between 5% and 10% for the other two needle samples. Considering that live needles' MC is 48% and dead and aged needles' MC is 7.5%, most of the mass loss before ignition of the live samples is due to water loss from drying. During flaming, between 80% and 90% of the sample mass is consumed and what is left are small char residues and mineral ash. After flaming, smouldering combustion of the residual char takes place and the mass loss rate is much lower.

Figure 4 shows measurements for the same three fuels under natural flow but in oven-dry state. The differences between the three fuels are smaller than for fresh conditions. The transient results under forced flow are not shown here (see [26] for details) but the fire parameters extracted in section 3.2 show that whereas the time to ignition is not affected by the flow conditions (differences within the experimental uncertainty), for aged and dead needles, the peak HRR is higher and the flaming time is shorter under forced flow.

3.2. Comparison of fire behaviour parameters

Table I reports the average and standard deviations of each fire parameters for all the repeats of the 80 experiments arranged in three categories (fuel type, moisture condition and flow condition). Measurements are repeatable with a 10% average variability. The most repeatable variables are the peak HRR, effective heat of combustion and time to ignition. The least repeatable variables are the mass loss and the CO/CO₂ ratio.

Figure 5 shows the times to ignition and flaming times. Whereas aged and dead needles behave similarly, live needles are substantially different with ~4 times longer times to ignition and ~75% longer flaming times. The effect of drying is only substantial in live needles and induces shortening of the ignition by a factor of ~2 and of the flaming times by ~75%. The effect of forced convection

[¶]Comparison of parameter values in the text is brief and indicative only, based on the average values. These comparisons are only mentioned in the text if the difference is significant based on the averages and the standard deviations of the two sets.

Table I. Summary of experimental results (average \pm standard deviation).

Flammability parameter	Fresh		Oven dry		
	Live	Aged	Live	Aged	Dead
Time to ignition (s)	59 \pm 3	13 \pm 1	13 \pm 2	11 \pm 1	9 \pm 0
Flaming time (s)	30 \pm 9	32 \pm 2	25 \pm 4	26 \pm 5	21 \pm 2
Normalized mass loss pre-ignition (g/g)	0.50 \pm 0.04	0.06 \pm 0.02	0.11 \pm 0.05	0.08 \pm 0.03	0.07 \pm 0.03
Normalized mass loss flaming (g/g)	0.39 \pm 0.04	0.77 \pm 0.04	0.68 \pm 0.10	0.69 \pm 0.07	0.73 \pm 0.06
Normalized mass loss postflaming (g/g)	0.09 \pm 0.05	0.15 \pm 0.02	0.18 \pm 0.07	0.21 \pm 0.05	0.18 \pm 0.03
Peak HRR (kW/m ²)	252 \pm 30	457 \pm 15	472 \pm 51	483 \pm 60	347 \pm 25
Effective heat of combustion (kJ/g)	11 \pm 1	20 \pm 1	20 \pm 1	21 \pm 2	21 \pm 1
Mean CO/CO ₂ ratio	0.07 \pm 0.07	0.15 \pm 0.07	0.02 \pm 0.01	0.12 \pm 0.01	0.02 \pm 0.01
Peak CO ₂ production (g/s/m ²)	19 \pm 2	35 \pm 1	36 \pm 4	37 \pm 5	27 \pm 2
Radiative fraction (kW/kW)	0.63 \pm 0.07	0.58 \pm 0.04	0.53 \pm 0.05	0.54 \pm 0.08	0.65 \pm 0.04
Natural Convection					
Time to ignition (s)	63 \pm 3	12 \pm 1	13 \pm 2	12 \pm 1	12 \pm 1
Flaming time (s)	34 \pm 11	16 \pm 2	18 \pm 5	18 \pm 2	13 \pm 2
Normalized mass loss pre-ignition (g/g)	0.43 \pm 0.03	0.06 \pm 0.01	0.08 \pm 0.04	0.10 \pm 0.03	0.08 \pm 0.01
Normalized mass loss flaming (g/g)	0.36 \pm 0.03	0.66 \pm 0.06	0.67 \pm 0.12	0.65 \pm 0.05	0.63 \pm 0.06
Normalized mass loss postflaming (g/g)	0.20 \pm 0.06	0.19 \pm 0.07	0.22 \pm 0.08	0.23 \pm 0.03	0.30 \pm 0.07
Peak HRR (kW/m ²)	212 \pm 15	625 \pm 29	632 \pm 34	468 \pm 24	457 \pm 23
Effective heat of combustion (kJ/g)	9 \pm 1	21 \pm 1	21 \pm 2	20 \pm 1	24 \pm 1
Mean CO/CO ₂ ratio	0.07 \pm 0.07	0.15 \pm 0.02	0.04 \pm 0.02	0.06 \pm 0.01	0.02 \pm 0.01
Peak CO ₂ production (g/s/m ²)	16 \pm 1	47 \pm 2	48 \pm 3	34 \pm 2	35 \pm 2
Radiative fraction (kW/kW)	0.50 \pm 0.04	0.59 \pm 0.05	0.57 \pm 0.04	0.62 \pm 0.07	0.64 \pm 0.05
Forced Convection					
HRR, heat release rate.					

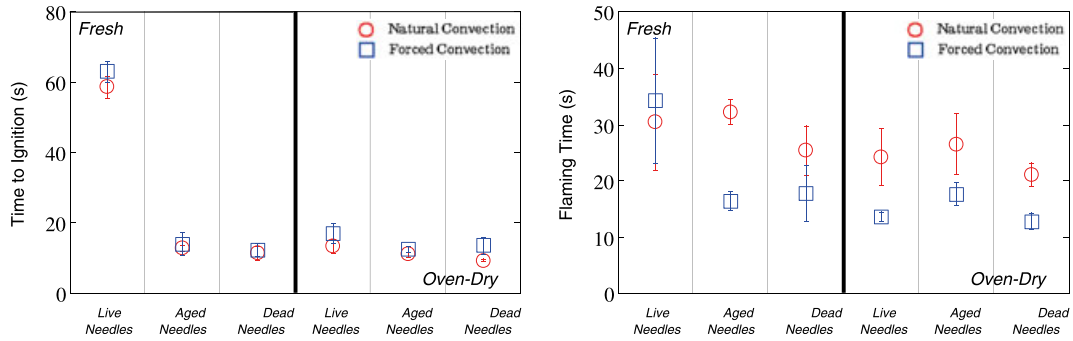


Figure 5. (Left) Time to ignition and (Right) flaming time.

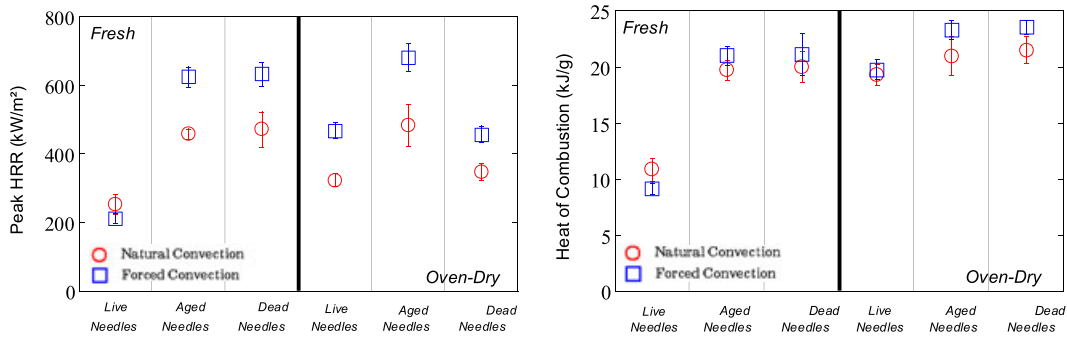


Figure 6. (Left) peak heat release rate and (Right) effective heat of combustion.

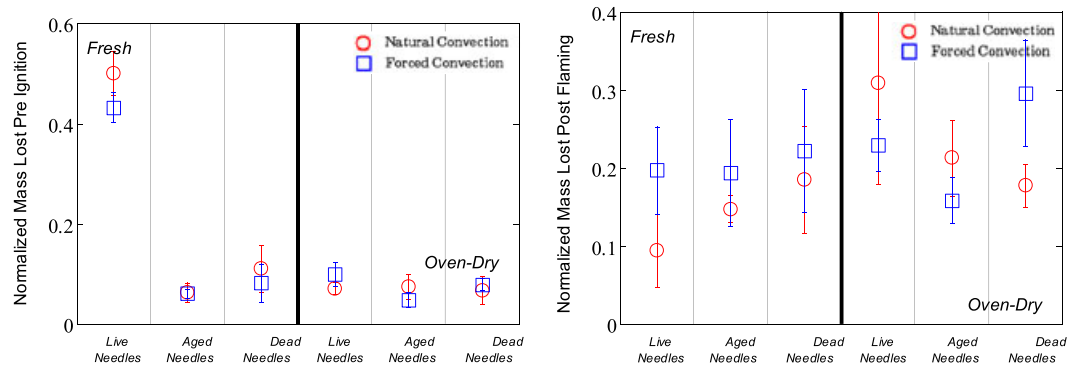


Figure 7. Mass loss during (Left) pre-ignition and (Right) postflaming regime.

is significant in the flaming times, which are decreased by ~60%, but it is not significant in the ignition times.

Figure 6 shows peak HRR and the effective heat of combustion. Overall, aged and dead needles behave similarly; whereas live needles display 60% lower peak HRR and 50% lower heats of combustion. A large part of this can be explained in terms of MC, but there is a noteworthy exception in dry samples: the HRR peak of live needles is similar to dead needles, but lower than aged samples. The effect of drying is large in live needles; it substantially increases the HRR and heat of combustion. Most interesting, drying decreases the peak HRR by ~30% of dead needles and suggests a degree of thermal degradation induced by the oven treatment, which is discussed later. The effect of convection is to increase the peak HRR (~40%) and the heat of combustion (~15%) and is most significant in aged and dead samples.

Figure 7 shows the mass loss (normalized to the initial mass) during the pre-ignition and postflaming stages. The former stage corresponds to pyrolysis in the absence of a flame, and the latter corresponds

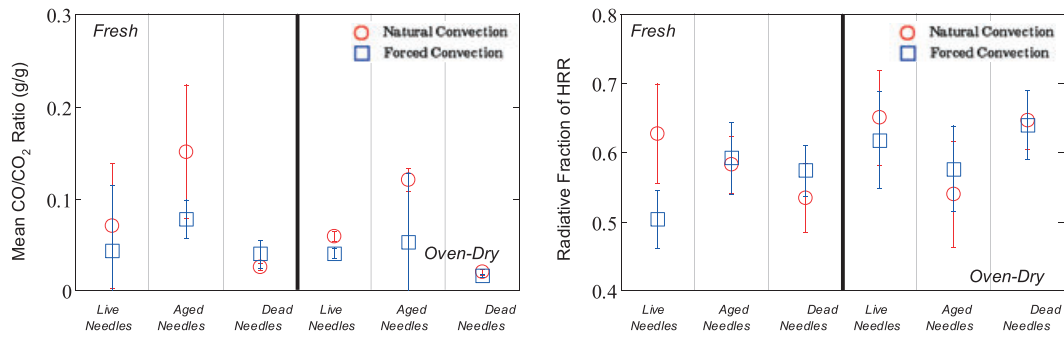


Figure 8. (Left) Mean CO/CO₂ ratio and (right) radiative fraction of heat release rate during flaming.

to smouldering combustion. Needles were not blown out of the sample holder pre-ignition or during flaming, but some small embers were airborne during smouldering. Most of the water evaporates during the pre-ignition stage, which is why the fresh live needles show the highest values of mass loss then. The effects of drying and flow are most significant during smouldering, which is expected because smouldering is controlled by convective transport of oxygen and heat losses (e.g. water evaporation) [33]. Live needles have the lowest amount of mass consumed during smouldering; however, the opposite happens in the dry state.

Figure 8 shows the CO/CO₂ ratio and the radiative fraction during flaming. Aged needles display the highest CO/CO₂ and a low radiative fraction, while live and dead needles are more similar to each other. The effect of drying is small on the CO/CO₂ and only affects substantially the radiative fraction under forced convection. The effect of convection is most notable on live samples. This suggests that fire dynamics does not follow a simple trend between live, aged and dead. The results show that there are fundamental differences in the physics and chemistry of the flames of these fuels.

Figure 9 shows scatter plots of data versus MC for the time to ignition and the peak HRR. The results confirm that MC explains most of the variability observed for the time to ignition, and a large portion of the variability of the peak HRR. The data set shows that other non-MC variables, like fuel type and flow condition, also contribute significantly to the variability of the peak HRR. The relationship of the time to ignition with MC is linear ($R^2 > 0.9$), and very similar trends are observed for both natural and forced flow conditions. Weise *et al.* [8] already reported this linear relationship for fine fuels. The observed relationship of the peak HRR with MC is not linear ($R^2 < 0.6$), and the trends for natural and forced flow conditions are significantly different. The results reveal a three-way coupling between burning behavior, MC and flow previously unreported and that can only be explained if plant chemistry and sample laboratory-drying are also considered.

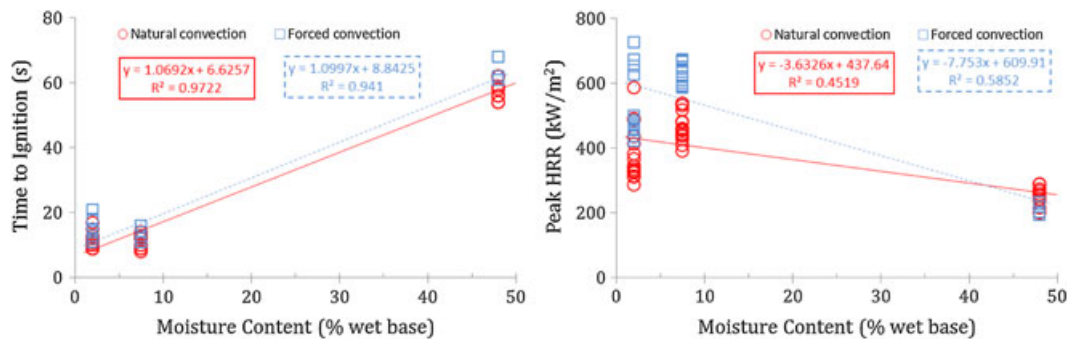


Figure 9. Scatter plots of variability of all data according to the moisture content: (Left) time to ignition and (Right) peak heat release rate.

4. CONCLUDING REMARKS

Our fire calorimetry results show good repeatability and demonstrate that the difference in burning dynamics of live and dead pine needles is significant and can be quantified and understood. The use of advanced calorimetry, in addition, allows measuring fire behaviour parameters not reported before for wildfire fuels, like radiative fraction and the CO/CO₂ ratio.

Overall, live needles ignite about four times slower, and burn with 60% lower HRR and 50% lower heat of combustion than dead needles. Aged needles closely resemble the behaviour of dead needles but the peak HRR, flaming times, CO/CO₂ ratio and radiative fraction were significantly different. Fresh live samples are the least affected by flow while dry samples the most affected. The results confirm the importance of MC in the burning behaviour of pine needles, but the differences between live and dead samples cannot be explained solely in terms of moisture. Our results show that there are fundamental differences in the physics and chemistry of the flames of these fuels and that fire dynamics does not follow a simple trend from live to aged and to dead fuels. In fact, it is already known that there is a significant difference in the carbohydrates stored in live and dead needles [34].

We observe that oven drying leads to large differences in the fire behaviour of live samples and that some of the difference cannot be explained only by the reduced MC. Aged and dead needles show smaller differences between them upon oven drying, but these are still significant in the peak HRR, CO/CO₂, radiative fraction and during the smouldering stage. This suggests that laboratory results are affected by the drying process in the oven, which induces important chemical and structural changes. This is most probably related, at least in part, to the loss of volatile organic compounds (VOC) inside the oven. In *P. halepensis*, the rate of VOC emissions like terpene increases with temperature [35]. Pappa *et al.* [36] and Statheropoulos *et al.* [37] reported that the thermal decomposition of *P. halepensis* needles in the range of 50–150 °C (specifically around the endotherm 88 °C) is attributed to the release of moisture and VOC. The release of moisture would explain the reduction in the ignition time and mass loss pre-ignition, and the release of VOC would explain the reduction in peak HRR, and the changes in CO/CO₂ and radiative fraction. Our results defy the common assumption that oven drying only affects the water content of samples (see [38] for an in-depth discussion on this assumption), or that the drying conditions are not important (see Jolly and Hadlow [39] and Jolly *et al.* [40] for an in-depth discussion on the effect of moisture on the chemical composition and flammability of live fuels). The fact that oven drying is widely used in wildfire laboratory studies merits more research.

The results reveal a three-way coupling between burning behavior, MC and flow previously unreported that can only be explained if plant chemistry and sample laboratory-drying are also considered.

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