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Experimental evaluation of bench-scale flammability of Ulex europaeus using a cone calorimeter

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Abstract

Wildfires have been causing considerable damage worldwide, and improving the ability to predict wildfire behaviour will ensure effective emergency response and keep ecosystems and communities safe. Increasing the understanding of factors affecting vegetation flammability is necessary for improving fire behaviour prediction models. This work investigates the influence of moisture content on the flammability of live and dead needles (0-3mm), twigs (3.1-6mm) and stems (6.1-10mm) of gorse (Ulex europaeus L.). Gorse is a shrub invasive in New Zealand, Chile and Western United States. In these countries, gorse poses a fire risk to nearby communities, as it contains flammable volatile resins, accumulates a substantial amount of elevated dead material, and grows in large masses, all of which promote fire ignition and growth. Gorse flammability was quantified with a bench-scale oxygen consumption calorimeter (cone calorimeter) with a focus on heat release rate. Supporting tests were performed on small sub-samples using simultaneous thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) to assess material-scale pyrolysis dynamics, providing fine scale information on the thermal degradation of each tissue type at the particle level.

The experimental methodology included investigation of the maximum moisture content at which each tissue type can ignite at 50 kW/m2, which is a reasonable approximation of the heat flux at the vegetation surface during fire front arrival in a shrub fire. Six moisture content levels from zero to the highest ignitable moisture content were then selected, and samples were conditioned in a climate chamber until the desired moisture content was reached. Three replicates of each tissue type were tested in a cone calorimeter at each moisture content. Flammability was assessed based on the heat release rate, total heat release, effective heat of combustion, residual mass fraction, time to ignition and combustion duration. Additionally, a small sub-sample of fresh live and dead needles, twigs and stems was analysed in the TGA/DSC apparatus. TGA/DSC results showed a different thermal degradation mechanism between live and dead fuel, with live tissue undergoing pyrolysis at a lower temperature than dead. However, the pyrolysis dynamics were not substantially different between needles, twigs, and stems, suggesting that the differences in their flammability attributes measured in the cone calorimeter are likely driven by physical characteristics such as surface-area-to-volume ratio rather than chemical composition. The results of this work contribute to the understanding of gorse flammability and the effect of moisture content and fuel structure on fire behaviour.

1. Introduction

In recent years, wildfires around the world have been increasing in frequency, intensity and duration (Jolly et al., 2015), leading to the loss of lives and property, and the destruction of ecologically important areas. Simultaneously with changes to the wildfire regime, a growing number of people are living in the wildland-urban interface (WUI) – the interface between the urban setting and the rural landscape such as lifestyle blocks (Andrew & Dymond, 2013), significantly increasing the potential damage from wildfires due to the proximity of people and property to large vegetated areas. More wildfires are entering the urban environment from the natural surroundings, such as the 2018 Carr Fire in Northern California (Lareau et al., 2018) and the 2017 Port Hills Fire in Christchurch, New Zealand (Pearce, 2018). In order to protect the growing WUI and make communities more resilient to future wildfire events, it is vital to understand fire behaviour and the complex interactions between fire, fuel (vegetation), weather and terrain in these environments. The current knowledge of how vegetation characteristics such as species, size, chemical composition and physiological properties affect wildfire behaviour (e.g. heat production, rate of spread, thermal radiation, etc.) is limited, and there is a need to increase our understanding of the physical and chemical dynamics of vegetative fuels commonly found in the WUI.

Gorse (*Ulex europapeus* L.) is a shrub native to Western Europe that has been introduced to other parts of the world (Kariyawasam and Ratnayake 2019), and is a prolific invasive species in some places such as New Zealand, Chile, and Western United States. Gorse poses a serious problem not only from a land management perspective, but also for wildfire management, as it occupies vast areas, often near populated centres (Figure 1), and burns readily. The flammability attributes of gorse and how they are affected by plant characteristics have not been extensively studied in the literature. Previous studies show that moisture content and surface-area-to-volume ratio are among the most important variables dictating plant flammability (White & Zipperer, 2010, Fares et al., 2017, Etlinger & Beall, 2004), and both of these characteristics vary spatially and temporally.

Figure 1 – Gorse shrubland on a hillside overlooking Christchurch, New Zealand

The flammability of vegetation is a complex phenomenon that encompasses attributes of the fuel's ability to initiate and propagate combustion. There are four main components of vegetation flammability: ignitibility, or the ease with which the fuel ignites; combustibility, or the rate at which combustion occurs; consumability, or the proportion of biomass that gets consumed; and sustainability, or the ability of the fuel to maintain combustion and produce energy (Anderson, 1970; Martin, 1994; White & Zipperer, 2010).

On one hand, oxygen consumption calorimetry is a relatively direct method for quantifying heat release rate (HRR) by measuring the amount of oxygen consumed per unit mass of fuel during the combustion of the sample. A cone calorimeter (Huggett 1980, Janssens 2002) is a bench-scale oxygen consumption calorimeter that creates a nearly uniform heat flux at the surface of a 10×10 cm^2 sample with a conical heating coil. A cone calorimeter measures all four flammability components: ignitibility as the time to sustained ignition, combustibility as the averaged and maximum heat release rate, consumability as the mass loss rate, and sustainability as the duration of heat release. Although all these components are considered in this study, emphasis was placed on the heat release rate, as it is considered to be the main attribute for describing fuel flammability (Babrauskas & Peacock, 1992; Madrigal et al., 2012), and can be used to indicate the extent of damage caused to the environment as well as the amount of energy available for igniting subsequent fuel and propagating the fire.

On the other hand, simultaneous thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) is a method that can give insight into the small-scale flammability dynamics of a solid fuel, tracking the mass loss rate of a small (~15 mg) sample in pure nitrogen while the temperature is increased at a consistent rate. Unlike with the cone calorimeter, measurements at this small scale provide insights into flammability characteristics that fundamentally affect fire behaviour. More specifically, variables such as particle size and moisture content are explicitly disregarded in the context of TGA/DSC measurements, so the results can be directly tied to other attributes such as live/dead condition of the sample. This technique is used in this study to complement and reinforce the analysis emerging from the cone calorimetry results.

The objectives of this research are to evaluate the effect of moisture content on gorse flammability, and to investigate the effect of condition (live and dead) and tissue diameter (needles, twigs and stems) of gorse on its flammability. These objectives are achieved by quantifying the heat release rate, effective heat of combustion, residual mass fraction, time to ignition and combustion duration of live and dead needles, twigs and stems at a range of moisture contents. Because of word-limit constraints, we only report cone calorimeter test results for a single moisture content of 7%, and results from TGA/DSC for a single heating rate of 20°C/min.

2. Materials and methods

2.1. Sample collection and classification

The flammability of six gorse tissue types was investigated, namely dead and live needles, twigs and stems using the cone calorimeter and the TGA/DSC apparatus. The samples were collected from a research site (43.461°S, 172.353°E) along the Waimakariri river, north of West Melton, New Zealand. The predominant vegetation at the site is gorse, with plant heights ranging from 40 to 200 cm. Plant material up to one centimetre in diameter was collected and separated into needles, twigs and stems based on diameter, with particles up to 3 mm classified as needles, material from 3.1 to 6 mm classified as twigs, and material from 6.1 to 10 mm classified as stems. The groups were further separated into live and dead condition based on the colour and general appearance of the material (Figure 3).

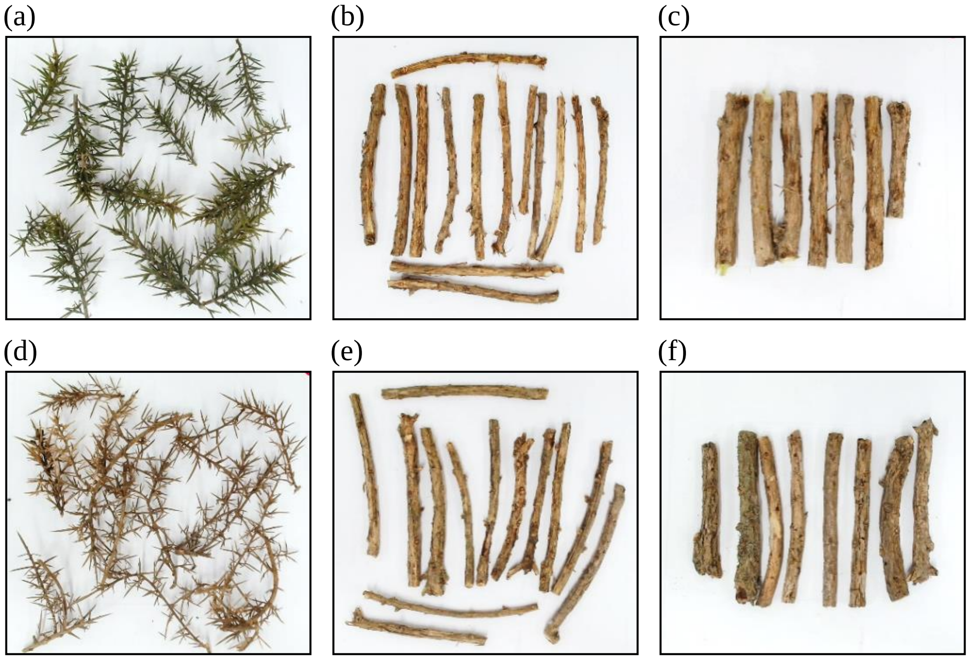

Figure 2 – Examples of six tissue types tested in the cone calorimeter and the TGA/DSC apparatus: live needles (a), live twigs (b), live stems (c), dead needles (d), dead twigs (e), and dead stems (f). The samples shown were prepared for testing in the cone calorimeter, and all have the apparent surface area of 70 cm².

2.2. Cone calorimetry

The collected plant material was trimmed to 10 cm lengths to fit into the 10×10 cm^2 sample holder of the cone calorimeter. Some material of each tissue type was placed into an environmental chamber to obtain a range of moisture contents, and ignition tests were performed on each tissue type to determine the maximum moisture content at which piloted ignition can occur at 50 kW/m^2. The heat flux of 50 kW/m^2 was chosen for ignition testing and cone calorimetry experiments because it is representative of the radiative heat flux at the vegetation surface at the time of fire front arrival in a shrub fire (Morandini & Silvani, 2010). Following the ignition tests, six moisture content treatment levels were selected to span the range from 0% up to the maximum ignitable moisture content, and three replicates of each tissue type at each moisture content were prepared for testing in the cone calorimeter, ensuring that the apparent surface area (the surface area of the sample exposed to the radiative heat flux from the cone heater) is consistent between samples.

Table 1 – Experimental design for the cone calorimetry tests and TGA/DSC tests, with 7% tissue moisture content for cone colometry samples, and variable moisture content representative of field conditions for TGA/DSC samples

3 tissue sizes		2 conditions		2 experiments		1 or 3 replicates
Needles Twigs Stems	×	Live Dead	×	Cone calorimetry	×	Rep 1 Rep 2 Rep 3
				TGA/DSC	×	Rep 1

The samples were tested in the cone calorimeter at 50 kW/m^2 in accordance with the ISO 5660-1 standard (ISO 5660-1, 2002), with the exception that a porous 10×10×2 cm^2 wire frame sample holder (Barboni et al. 2017) was used to ensure that testing conditions are representative of field conditions. The surface area exposed to the cone heater element was kept at 70 cm^{-2} for all tissue types to ensure similar heating and ignition conditions. Because of word-limit constraints, we only report results from cone calorimeter test for a moisture content of 7%. Mass of the samples varied between the experiments as follows: 3.05 to 4.5g for needles, 12.9 to 15.7g for twigs, and 25.2 to 31g for stems.

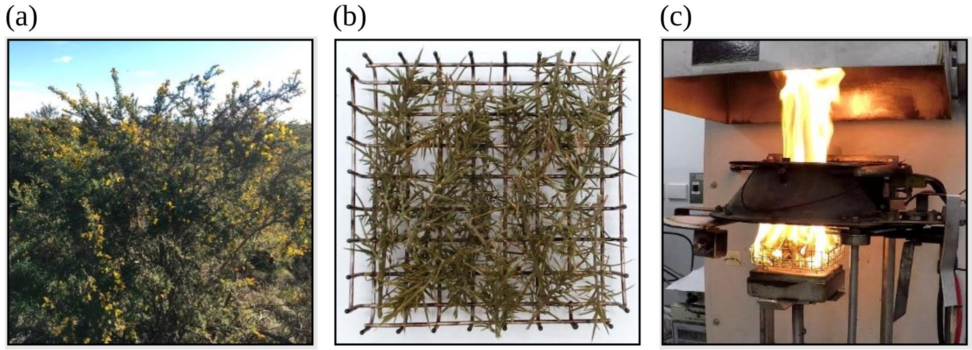

Figure 3 – Gorse plant at the field site (a), gorse needles in a sample holder prepared for the test in the cone calorimeter (b), and gorse needles during the test (c)

2.3. Simultaneous differential scanning calorimetry and thermogravimetry

SDT Q600 manufactured by TA Instruments was used to investigate the thermal decomposition behaviour of gorse needles under nitrogen environment. The equipment was calibrated following manufacturer's instructions for weight, temperature and heat flow at the tested heating rate. Fresh gorse samples were ground using a sample grinder and sealed in air-tight plastic containers for testing within 24 hours. Approximately 15 mg of ground sample was placed inside a 90 µL alumina cup, applying a dynamic heating mechanism from 20 to 1200°C at 20°C/min. The relative sample weight was calculated by dividing the raw weight by the weight of the sample at 185°C once all the cellular water evaporated and the mass loss rate stabilized.

3. Results

The heat release rate curves measured with the cone calorimeter for the six tissue types at 7% moisture content are presented in Figure 4. The pattern of heat release rate varies between tissue types, providing a good basis for comparing their overall flammability. Tissues of smaller diameter ignited faster and burned more vigorously, reaching their peak heat release rate faster than larger size classes, while larger particle sizes were associated with delayed ignition, longer burning and decay stages of combustion, and greater total energy production.

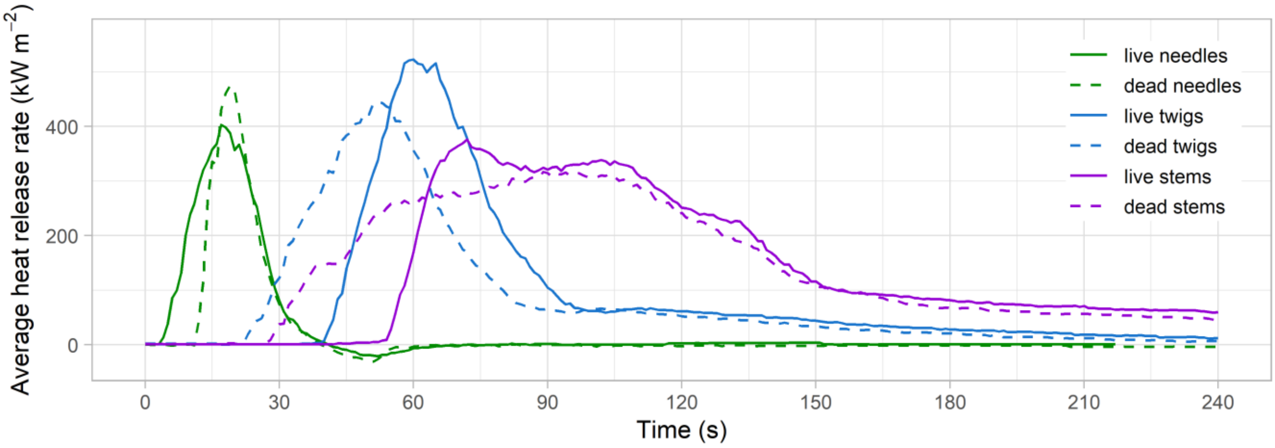

Figure 4 – Heat release rate for gorse needles with 7% moisture content as a function of time since the start of exposure to the radiative heat flux of 50 kW m^{-2}. Three replicates of each tissue type were tested, and their results were averaged into one curve for readability.

Flammability attributes derived from the heat release rate data are summarised in the top row of Figure 5, and attributes manually measured in the lab during testing are shown in the bottom row of the figure. Total heat release ranged from 50.6 kJ to 502 kJ for all tissue types at the studied moisture content. The effective heat of combustion ranged from 13.7 to 18.1 kJ g^{-1}, which is similar to the 12 to 17 kJ g^{-1} range observed for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees with 5 to 15% moisture content (Babrauskas, 2006). Peak heat release rate, a measure of combustibility, increased with decreasing particle size, and ranged from 318 to 613 kW m^{-2} across tissue types. This is similar to values found in literature for different species such as 400 kW m^{-2} for dead litter of *Pinus pinaster* (Madrigal et al., 2011) obtained using mass loss calorimetry, and 550 to 1050 kW m^{-2} for dead leaves and twigs of *Cistus monspeliensis* 0.75 to 3mm in diameter (Barboni et al., 2017) obtained with a cone calorimeter. Time to ignition, a measure of ignitibility, and combustion duration, a measure of sustainability, increased with increasing particle size. Time to ignition ranged from 8 to 59 seconds, while combustion duration ranged from 10 to161 seconds respectively. Time to ignition for individual tissue types was comparable to values found in literature. For instance, time to ignition for live and dead twigs measured in this study was between 23 and 51 seconds, while the time to ignition for oven-dried leaves and twigs of Montpellier cistus (*Cistus Monspeliensis* L) from existing literature was 35.7 ± 5.8 seconds. Residual mass fraction ranged from 0.0236 to 0.077 g g^{-1}, and was considerably higher for dead tissue compared to live tissue. Further experiments are required to gain insights into this trend.

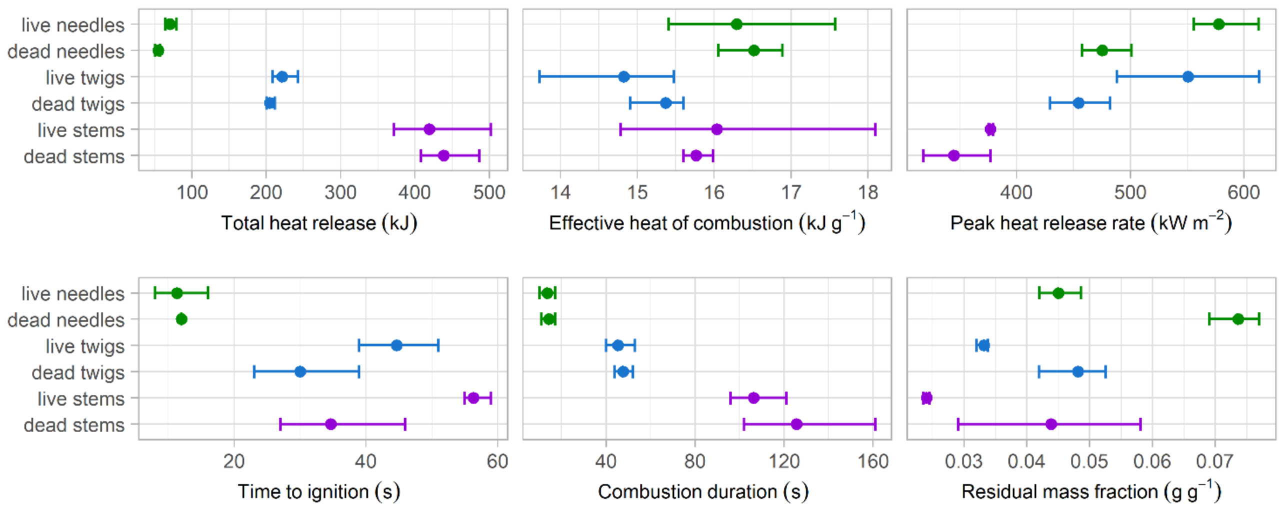

Figure 4 – The mean and range of flammability attributes measured with the cone calorimeter. The whiskers indicate the minimum and maximum values measured for the three replicates, and the point indicates the mean

The mass loss rate of small (~15 mg) ground samples of the six tissue types measured in the TGA/DSC apparatus is presented in Figure 6. The peak mass loss was greater for the live needles, twigs and stems (1.14, 1.02 and

0.904 % °C^{-1} respectively) compared to the dead needles, twigs and stems (0.61, 0.78 and 0.74 % °C^{-1} respectively). The peak mass loss also generally occurred at a lower temperature for the live needles, twigs and stems (93, 356 and 350 °C respectively) than for the dead needles, twigs and stems (366, 371 and 348 °C respectively). The varying slope before the decomposition peak and the subsequent plateau and perturbations after the decomposition peak for all tissue types indicate that gorse tissues consist of multiple material components, which thermally decompose across overlapping temperature range.

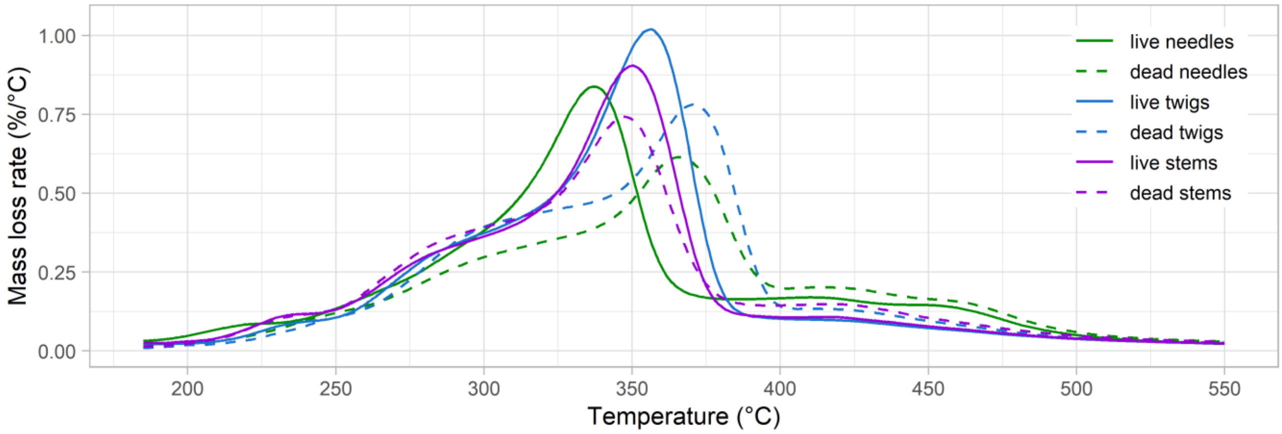

Figure 6 – TGA/DSC results: mass loss rate as a function of temperature at the heating rate of 20 °C/min

The pyrolysis dynamics were not substantially affected by particle size for live material, as the degradation rate and temperature peaks were around 350°C, suggesting that the differences in flammability attributes measured in the cone calorimeter are likely driven by physical characteristics such as surface-area-to-volume ratio rather than chemical composition. Generally, dead material showed higher peak temperature, suggesting lower flammability potential, which can be associated with the differences in the volatiles content.

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