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# A methodology for comparing the relative effectiveness of suppressant enhancers designed for the direct attack of wildfires

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A B S T R A C T

Suppressant chemicals are often added to water for use in the direct attack of wildfires to extend the longevity and suppression effects of the water. There are a range of suppressants available, however there has been limited testing to determine which are the most effective. This paper presents an experimental methodology designed to enable the comparison of the relative effectiveness of wildfire suppressants applied in direct attack to fires in forest fuels. The method involves suppressants being applied onto the flaming fronts of standardised laboratory fires burning in uniform forest litter fuels within a wind tunnel through a pressurised system mounted above the burning fuel. The minimum volume of suppressant required to extinguish a standard fire is determined and used to quantify suppressant effectiveness. Examples of the method are presented for plain water and water with three types of wildland fire suppressant. Results show that repeated tests conducted with the same suppressants have low variability (coefficient of variation ~10.8%) and thus high reliability. In order to minimise effects of non-controlled variation in fire behaviour between tests, results can be normalised to produce relative values for comparison across datasets.

## 1. Introduction

Wildfires, particularly fast-moving high-intensity fires, are a major threat to the safety of communities around the world and can have significant environmental and economic impacts from which it can take years to recover [1]. When a fire is actively burning, direct or indirect attack are the only options for attempting to limit its spread. While indirect attack (often the removal of fuel between the flaming edge and a predefined fireline) can be effective, it is a passive strategy that requires the fire to burn up to the modified fuel and runs the risk of being in the wrong location if carried out too far in advance of the fire and the fire changes its direction of spread as a result of an unexpected change in wind direction [2]. Direct attack, on the other hand, is an active suppression strategy that aims to extinguish the flaming edge, most often through the use of plain water or water with chemical additives. This tactic removes heat from the fire through water's high heat capacity and latent heat of evaporation, dilutes the oxygen available for reaction and applies an insulating layer to form a barrier between the fuel and oxygen [3]. Suppressants are typically delivered directly onto burning fuel from ground and air based firefighting resources.

Water is the most common agent for direct wildfire suppression due to its availability, low cost, ease of delivery, non-toxicity and effectiveness as a coolant [4,5]. However, many of its advantages also limit its capacity to extinguish flames. For example, the surface tension of water restricts its ability to coat fuels and it evaporates easily (particularly under the hot dry windy conditions associated with wildfires). During emergency situations an increase in suppression effectiveness can potentially have major benefits in reducing the time taken to extinguish wildfires, thereby limiting the resulting damage and area burned. Chemical additives are often mixed with water to increase its suppression effectiveness.

There are two main types of chemical additives used in wildfire fighting: retardants and suppressant enhancers. Retardants are comprised of inorganic salts (mainly ammonium phosphates) that inhibit flaming combustion and can slow fire progression even when the water used to deliver them has evaporated [6,7]. Retardants are typically used in indirect attack and applied from aircraft where they coat unburned fuels in the path of a spreading wildfire [8]. Suppressant enhancers added to water improve the suppression effectiveness of water by modifying its physical attributes.

Two main classes of suppressant enhancers are commonly used on wildfires. The first is foaming agent, which employs surfactants to reduce the surface tension of the water, enhancing its coverage of fuel particles and prolonging its wetting effect [9–13]. Foaming agent also allows air to mix with the water forming an insulative foam barrier

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between the fuel and the fire [14,15].

The second class of suppressant enhancer is gel (also referred to as water enhancer [16]). This additive is comprised of cross-linked hydrophilic superabsorbent polymers which have the capacity to absorb up to 700 times their own mass of water [17–20]. Gel additives increase the viscosity of water, increase adherence to fuels and minimise drift and dispersion when dropped from aircraft [16].

A significant amount of work has been undertaken to investigate the effectiveness of wildfire retardants through a range of analytical laboratory tests, wind tunnel fire spread tests and field observations [6]. These studies have been motivated by the high costs associated with their use [21]. Investigations of retardant effectiveness on wind tunnel fires have been the main focus of retardant evaluation and have involved comparative observations of rate of spread and fuel consumption in controlled conditions within a wind tunnel [7,21–25]. Wind tunnel retardant effectiveness tests have developed into standard methodologies for evaluating commercially available products for wildland fire agencies in conjunction with a range of other tests investigating toxicity and corrosivity [24,26]. Other retardant effectiveness studies have investigated the combustion recovery of wind tunnel fires when retardant mixes were applied directly onto flames [27,28].

There has been much less work investigating the effectiveness of suppressant enhancers for wildland fire suppression or developing standards methodologies for such investigations. Most of this work has considered the role of suppressant enhancers in the protection and their ability to adhere to buildings and vegetation [29–32]. One field study [33] considered the effect of indirect application of foam and retardant on the progression of shrubland fires and found both to significantly reduce fire spread, though there were limited details published. The direct suppression of moving fires in wildland fuels has only been considered in two related published studies [34,35]. These studies aimed to determine the depth of suppressant required to extinguish small-scale pine litter fires in a sheltered outdoor environment. These experiments used a moving spray system mounted above a fuel bed to simulate the delivery of suppressant from an air-tanker onto fires burning in reconstructed pine litter and slash fuels. A range of coverage depths (0.2–5.8 mm) were applied to the fires which were exposed to ambient conditions with light winds ($< 0.9\ m\ s^{-1}$). The extinction effect was assessed using the persistence of burning for 20 min following suppressant application. These experiments were used to derive linear equations predicting the suppressant depth required to extinguish fires of different fireline intensities (63–996 $kW\ m^{-1}$) and recommended coverage levels for air-tanker drops [35]. The results of these experiments have also been used to validate theoretical calculations estimating the minimum amount of suppressant required to extinguish fires [4].

Over the past two decades there has been an increased use of aircraft for the direct suppression of wildfires, particularly when conditions are beyond the direct attack capability of ground resources [36,37]. With the relatively high operating costs and challenging logistics of using such suppression resources, suppressant enhancers are often added to the water carried by aircraft to enhance the suppressive effect of the firefighting load to maximise its efficiency and cost-effectiveness. There are a large number of suppressant enhancers available and these can be prepared at a variety of concentrations for a potentially broad range of direct attack applications. Currently there are no standard methods for testing the direct suppressive effectiveness of suppression chemicals on wildfires, with existing suppressant selection criteria focussed on other aspects such as toxicity, biodegradability, corrosivity, physical properties and adherence to surfaces [13,16]. The lack of a standard method for assessing direct suppressive effectiveness is probably due to the historically higher usage of retardants from aircraft. The availability of a standard testing methodology would allow fire agencies to compare available suppressant mixes in a way that is robust and reliable and enable informed product selection decisions that maximise suppression cost-effectiveness.

This paper proposes a method for comparing the direct suppressive effectiveness of wildfire suppressant enhancers. The method uses the direct overhead application of suppressant mixes onto a standardised and repeatable free-moving fire front burning in representative heterogeneous forest surface fuels within a combustion wind tunnel. Suppressant enhancer effectiveness was evaluated using the quantity of suppressant required to extinguish flaming combustion and stop the spread of a standard evaluation fire. Examples using a random selection of commercial suppressant enhancers, foaming agent and plain water are presented to demonstrate the methodology and its repeatability.

## 2. Background

The majority of the work investigating wildfire retardant effectiveness has involved comparative laboratory experiments with fires burning in treated or untreated fuels. Field experiments and observations of wildfire operations undertaken to investigate suppression effectiveness are difficult to organise and conduct [37–39] and provide limited datasets suitable for robust statistical analysis. In contrast, experiments conducted in combustion wind tunnels can be used to investigate the relationships between influential variables in greater isolation from each other and variation in potentially confounding factors can be minimised [40]. This setting also allows safe close range observation of events and processes, can incorporate a higher degree of instrumentation and offer a greater potential for experiment replication, which is essential for comparative testing. While the scale of combustion wind tunnel fires is much smaller than fires in the field, their combustion processes are similar and their results informative.

Studies of wildfire phenomena using combustion wind tunnels employ either artificial (i.e. constructed) fuels such as excelsior or naturally occurring fuels such as pine needles or straw. Artificial fuels are often used because they are highly homogenous and expected to result in uniform and repeatable fire behaviour when burnt. However significant effort is required to relate results in these fuels to natural wildland fuels [40]. Natural fuel beds comprised of heterogeneous particles have more variable particle types and sizes which are more representative of surface fuel layers found in the field [40,41]. A recent study of the repeatability of fires burning in heterogeneous pine and eucalypt litter fuel beds within a combustion wind tunnel [40] found that they do not inherently introduce significant variability in fire behaviour or have high residual error requiring large numbers of replicate experiments.

There are two primary options that could be employed to evaluate the performance of direct suppression on combustion tunnel fires. First, a standard volume of suppressant could be applied onto the flame front, with suppressant effectiveness assessed using the change in behaviour, as measured by reduction in rate of spread or the duration that fire spread is held before it resumes. This method of assessment would need to be conducted with a range of suppressant volumes applied in separate tests in order to produce results that could be used to compare suppressants with highly different holding characteristics.

The second evaluation option is to determine the suppressant volume required to extinguish a standard fire by applying incremental volumes until the fire is extinguished. This option can be used to rank quantitatively the performance of each suppressant tested. The second option was selected for this study because it provides a precise means of comparison between suppressant mixes and directly relates to the common objective of direct wildfire suppression, which is to stop fire progression. However, this option requires a highly consistent (i.e. 'standardised') source of fire on which to be applied.

In order to achieve a repeatable and suitable fire environment, a combustion wind tunnel was used with reconstructed natural fuel beds consisting of forest surface litter sourced locally. A single constant air speed provides consistent fire behaviour conditions for comparative studies.

## 3. Apparatus

### 3.1. CSIRO Pyrotron combustion wind tunnel

The methodology presented here was developed in the CSIRO Pyrotron, a contractionless wind tunnel designed for the controlled laboratory study of the combustion of natural wildland fuels [42]. The Pyrotron consists of a large (1.37 m diameter) centrifugal fan that pushes air through a diffuser and settling section before it reaches a large working section where experiments are conducted. Fuel is laid on the ceramic heat-resistant tile floor which can accommodate a fuel bed up to 1.5 m-wide and 4.8 m long. The combustion tunnel provides a high degree of air flow uniformity and low turbulence across the working section enabling consistent fire behaviour within and between repeated experimental conditions [40].

Air is drawn in from the outside environment and is subject to ambient atmospheric conditions; as a result experiments are scheduled to be conducted when these are within a suitable range (air temperature > 20°, relative humidity < 50%). The main effect of variable ambient air conditions is to change the equilibrium moisture content of the fuel. This effect can be ameliorated by conditioning the moisture content of the fuels through the use of a dehydration oven, where fuels are dried to pre-determined uniform equilibrium moisture content before being laid out in the working section and a suppression test conducted.

### 3.2. Suppressant application system

A suppressant application system was designed to apply suppressant across the width of the fuel bed from a flat spray nozzle. Overhead application was used to simulate aerial drops of suppressant. This approach has been used in previous wildfire suppression [34,35] and retardant studies [7,21,22,24,27,28] and is commonly used in studies investigating the suppression of static fires [43–46].

The suppressant application system consisted of a pressurised 10 litre stainless steel tank with a remotely controlled solenoid valve connected to an outlet line and spray nozzle mounted in the Pyroton ceiling (Fig. 1). The holding tank was rated to 250 kPa and its pressure could be adjusted using an air compressor and regulator. The tank was able to quickly re-pressurise following suppressant release. A range of flat spray nozzles were trialled, with one (Teejet 8030) able to spray suppressants with a range of viscosities (1–600 cP) consistently across the 1.5-m-width of the fuel bed providing that a suitable tank pressure was used. The system pressure was individually calibrated for each suppressant to spray across the full width of the fuel bed. The resulting deposition pattern consisted of a distinctive line across the width of the fuel bed that had a sharp edge on the upwind side where the majority of suppressant was deposited and less distinctive downwind edge where some suppressant spray drifted in the air flow. The distance that different suppressant mixes drift downwind of the spray nozzle varies and is likely to depend upon characteristics such as surface tension, viscosity and droplet size.

## 4. Methodology

A standard procedure was developed for suppressant evaluation tests, with a single suppressant mix used each time. The example results presented here demonstrate the methodology and do not provide conclusive comparisons of the suppressants trialled as each suppressant mix was only trialled at a single concentration (i.e at or within the product supplier's recommendations) (Table 1). The tank pressures required to span the fuel bed varied considerably due the large range of suppressant viscosities.

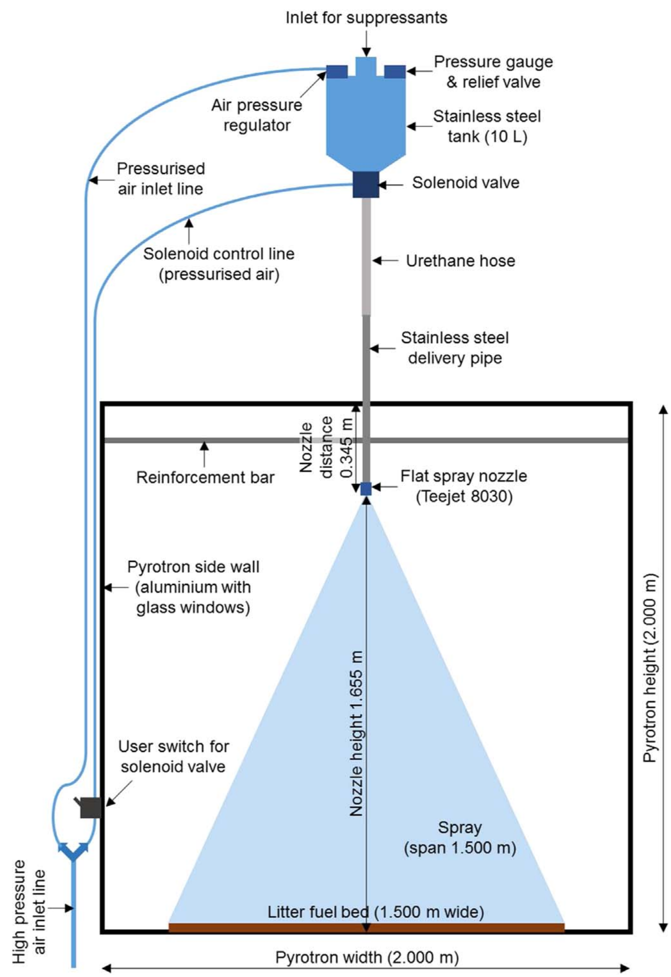


**Fig. 1.** Schematic diagram showing suppressant application system and cross section of Pyrotron working area viewed end-on (i.e. fire spread is out of the page).

Concentrates of example suppressants were prepared with tap water in clean plastic buckets. The water was agitated using paint mixing paddles attached to an electric drill while the concentrate was slowly added. The liquid concentrates were shaken prior to mixing to ensure that they would be prepared at the desired concentration. The density of each of the mixed suppressants was determined from three 50 mL samples.

The location of the upwind edge of the main line of suppressant on the fuel surface was measured for each suppressant and tank setting before the Pyrotron was setup for fire suppression tests. This was done using the same experimental setup but with the suppressant landing on a dry rubber mat with location markers on the floor of the Pyrotron. These measurements enabled the critical location for suppressant application on the head fire to be pre-marked for each suppressant evaluation test. The flow rate for each suppressant mix was determined prior to evaluation tests by collecting the suppressant released over a known period (~5.0 s), weighing it and calculating the volume released using the suppressant density. The flow rate was used to determine the suppressant volume released during each test.

We selected litter from a local dry eucalypt forest as our fuel in order to represent typical fuels in Australian forests (*Eucalyptus rossi* and *E. macrorhyncha* collected from Kowen Forest east of Canberra, ACT, 35° 19.5'S, 149°15.3′E). Fuel beds were constructed from sorted eucalypt litter (fallen leaf, bark and twigs < 6 mm diameter from which decomposing layers, broken fragments and inorganic material had been removed). Each fuel bed was three metres long and 1.5 m wide.

The fuel load selected for this methodology was 1.2 kg $m^{-2}$ (12 t $ha^{-1}$), which represents the equilibrium fuel condition of an average

**Table 1**
Characteristics of suppressant used in example tests.

| Suppressant | Number of evaluation tests | Concentration (%)[a] | Density of mix (kg $m^{-3}$) | Viscosity (cP)[b] | Tank pressure (kPa) | Mean wind drift distance[c] (m) |
|---|---|---|---|---|---|---|
| Control (no suppressant) | 3 | NA | NA | NA | NA | NA |
| Water | 5 | 0 | 1.00 | 0.95 | 25 | 0.20 |
| Foam | 4 | 0.4 | 1.00[d] | 0.86 | 25 | 0.35 |
| Gel (liquid concentrate) | 3 | 1.2 | 0.95 | 590 | 220 | 0.25 |
| Gel (granular concentrate) | 3 | 0.72 | 0.99 | 40 | 85 | 0.15 |

[a] Measured in percent volume for the liquid concentrates and percent mass for the granular concentrate.
[b] Measured with a piston-style electromagnetic viscometer (Cambridge Viscosity VISCOlab 4000).
[c] Horizontal distance between the spray nozzle and main line of suppressant on the Pyrotron floor.
[d] Measured as mixed concentrate in water prior to being aerated during spraying.

dry eucalypt forest [47]. The fuels were conditioned in a large dehydration oven at a temperature of 35 °C for a minimum of 24 h to obtain an equilibrium moisture content of about 7% oven-dry weight, which is representative of moderate to high wildfire conditions [48,49] and is within the range that has been used in other combustion wind tunnel experimental fires [22,28,41,47,50,51].

The conditioned fuel was distributed evenly across the Pyrotron floor up to 15 min prior to ignition to prevent the pre-conditioned fuel responding to ambient conditions (i.e. to maintain a moisture content close to 7%). The fuel for each burn was transported from the oven in six boxes with the contents of each placed on a corresponding area of the fuel bed to ensure consistent distribution. Previous analyses of fuel beds prepared in this way have found them to have depths of 17.7 (+/-0.2) mm and bulk densities of 68.9 (+/-0.8) kg $m^{-3}$[47]. The fuel bed was bordered by the ignition bar on the upwind edge and on the sides metal edging 20 mm tall to define the width of the fuel bed.

The spray nozzle was installed above the centre of the fuel bed, two metres downwind from the ignition line (Fig. 2). This distance was selected as previous experiments had shown that fires were able to attain a quasi-steady rate of spread within two metres of a line ignition within the Pyrotron [47]. The 1.0 m of fuel bed downwind of the nozzle allowed for any drift in the suppressant sprays to be monitored..

A cotton string line was placed on the fuel bed to provide a visual cue of where the bulk of suppressant would land. This was based on the spray distance measurements made using the same suppressant, tank pressure and Pyrotron fan setting. Three random samples of litter (20–30 g) were taken up to five minutes prior to ignition to determine the fuel moisture content (FMC) at the time of the test. The Pyrotron fan was set to generate a 1.63 m $s^{-1}$ airflow over the fuel bed for all test fires.

All test fires were ignited as a 1.5 m-long line using 120 mL of ethanol in a ‘v’-shaped ignition channel positioned perpendicular to the air flow on the upwind edge of the fuel bed (Fig. 2). The fires burnt through untreated fuel for a minimum distance of 2.1 m before reaching the reference string line. Rate of fire spread was measured as the time taken for the fire to travel between 1.5 and 2 m (as measured from the ignition line) using the array of thermocouples spaced every half metre on the floor of the Pyrotron [40,42]. This interval provided an estimate of the rate of spread of the fire immediately upwind of the suppression location that is unaffected by the acceleration phase of a fires apparent immediately after ignition [40,42].

The suppressant application system was activated to provide an initial short burst (~1–2 s) of suppressant directly onto the flames once the base of the flame front (normally in the centre of the fuel bed) reached the cotton string line (Fig. 3a). Subsequent spray bursts were repeated every five to thirty seconds until forward spread and flaming combustion were observed to stop and the fire remained extinguished. Assessments of fire sustainability were made between each burst with further spray bursts applied when flaming combustion was observed along the forward edge. The period between bursts generally increased with time as flames often reappeared a few times following suppressant application and a period of residual glowing combustion. This process ensured that a minimum volume of suppressant was applied during

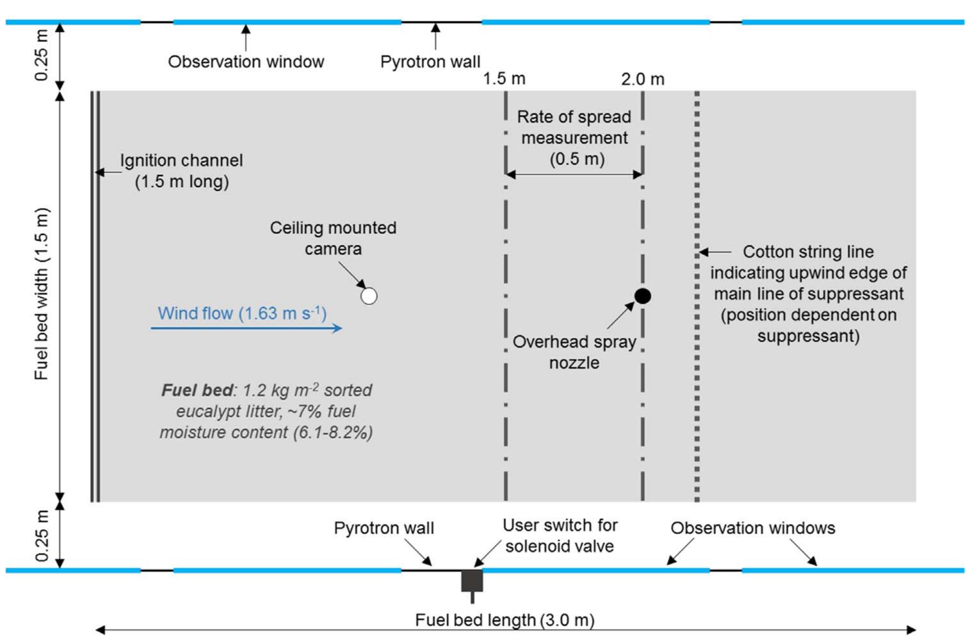


**Fig. 2.** Plan view of fuel bed and experimental setup in the CSIRO Pyrotron. Fire spread is from left to right.

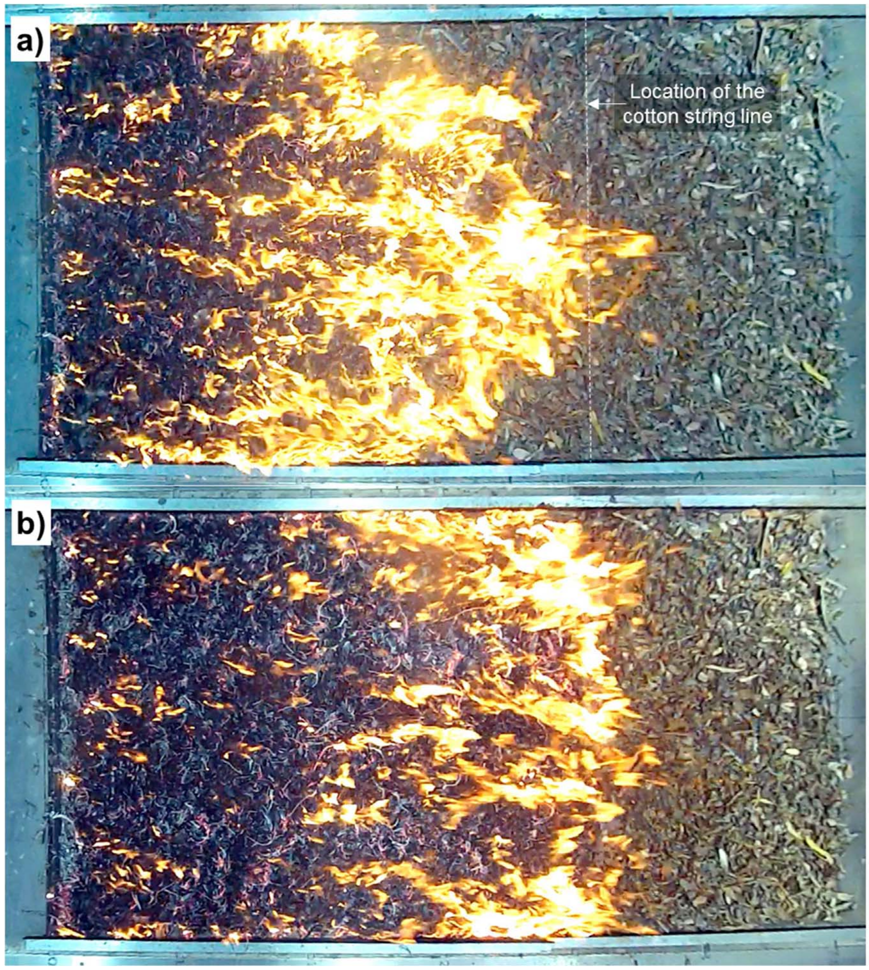


**Fig. 3.** Overhead view of suppressant evaluation test fires burning from left to right (a) immediately before suppression and (b) during suppression application. Note the change in the overall shape of the fire as suppression stops forward spread of the head.

each test.

As the flame front was pointed (Fig. 3a) and the suppressant spray pattern straight, only the leading section of the fire was directly hit during the initial spray burst. Flank fire sections (i.e. fire edge to either side of the head) burned into the wetted fuels and were directly hit during subsequent bursts (Fig. 3b). A stopwatch was used to measure the duration that the suppression application system was activated. The volume of suppressant used in each test was then determined from the total application time and the predetermined suppressant flow rate. Other options for quantifying the volume used in each test, such as measuring the volume in the tank before and after, were not used because of the considerable effort required to install and remove the tank and the potential for spilling contents around electrical equipment.

## 5. Results

Here we present the results from 15 evaluation tests used to provide examples of the methodology. These tests were undertaken using plain water, a foam mix and two gel suppressant enhancer mixes (Table 1). Data from three control evaluation tests where no suppressants were applied were also undertaken to provide further fire behaviour comparisons (and to ensure consistency in fire behaviour).

The 18 evaluation fires exhibited a low variability in rate of spread prior to suppressant application, with a standard deviation of $0.005\ \mathrm{m\,s^{-1}}$ around the mean of $0.036\ \mathrm{m\,s^{-1}}$ (14% coefficient of variation) (Table 2). Rate of spread was not significantly correlated with relative humidity (r=−0.291, p=0.242) or ambient temperature (r=0.373, p=0.128), but was negatively correlated with FMC (Fig. 4, r=−0.604, p=0.008). This is a result of fuel moisture content being influenced by both temperature (r=0.574, p=0.013) and relative humidity (r=0.483, p=0.042) in the laboratory, as has been observed in previous studies [40,47].

The volume of suppressant required to stop and extinguish the 15 suppressant evaluation fires was correlated with rate of spread (r=0.534, p=0.040, Fig. 5a) but not significantly correlated with FMC (r=−0.377, p=0.166, Fig. 5b). These correlations are masked by the effect of suppressant type, as can be seen by the distribution of suppressant type points in Fig. 5 which shows distinct bands of volume used for the different suppressant types. The relationships between suppressant volume used and rate of spread (Fig. 5a), and rate of spread and FMC (Fig. 5b), show that generally fires in drier fuels burn more quickly and require larger quantities of suppressant for extinction.

Each of the suppressant types tested had narrow and distinctive distributions of suppressant volume required for extinction (Fig. 6a). The suppressant volumes used in each test were normalised for rate of spread in order to remove any effect variation in rate of spread would have on the results. The normalisation was performed using the ratio of overall mean rate of spread ($0.036\ \mathrm{m\,s^{-1}}$, Table 2) to the observed rate of spread for each fire (Eq. (1)) with raw and normalised results summarised in Table 3..

$$Vol_{norm} = Vol_{obs} \times \frac{R_{mean}}{R_{obs}} \tag{1}$$

where *Vol* is the volume of suppressant required to suppress a fire,

**Table 2**
Conditions during example tests, mean [range].

| Suppressant | Temperature (°C) | Relative humidity (%) | Fuel moisture content (%) | Rate of spread (m $s^{-1}$) |
|---|---|---|---|---|
| Control (no suppressant) | 24.9 [24.5–25.3] | 29.0 [23.0–37.9] | 6.9 [6.1–7.7] | 0.036 [0.028–0.047] |
| Water | 25.7 [24.2–27.8] | 30.5 [25.8–45.3] | 7.1 [6.4–7.8] | 0.038 [0.035–0.041] |
| Foam | 25.0 [23.7–26.6] | 40.3 [33.4–48.0] | 7.0 [6.3–8.0] | 0.037 [0.033–0.043] |
| Gel (liquid concentrate) | 23.8 [23.3 2.6] | 32.7 [24.1–48.3] | 7.5 [6.9–8.2] | 0.034 [0.034–0.034] |
| Gel (granular concentrate) | 24.9 [24.3–25.5] | 23.9 [21.5–27.9] | 7.3 [6.4–7.8] | 0.034 [0.032–0.036] |
| All | 25.0 [23.3–27.8] | 31.7 [21.5–48.3] | 7.2 [6.1–8.2] | 0.036 [0.028–0.047] |

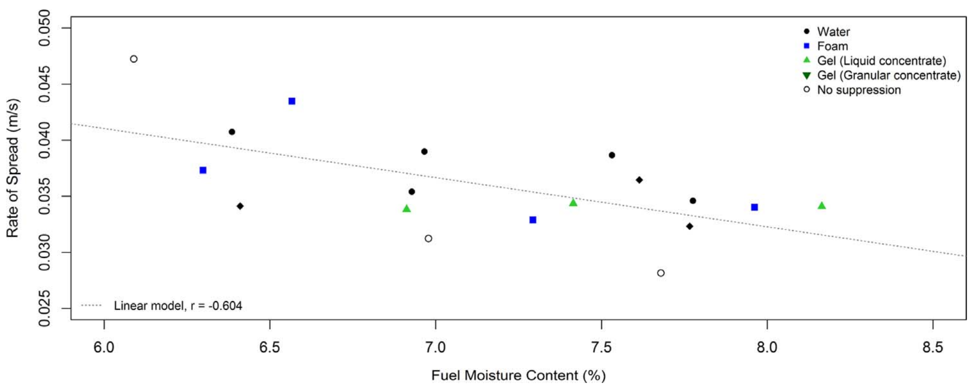


**Fig. 4.** Observed correlation between fuel moisture content and rate of spread during suppressant testing.

subscript *norm* indicates a normalised value, subscript *obs* indicates an observed value, and subscript *mean* indicates the mean of all observed values.

The results for the normalised suppressant volume data (Fig. 6b, Table 3) are very similar to those for the raw data with the main difference being the reduced coefficient of variation for each suppressant with the exception of granular gel concentrate. Overall there was a slight reduction in the mean and spread of volume of water and foam required for suppression and a slight increase in mean volume of the gels, with the spread of the liquid concentrate volumes remaining unchanged and the spread of granular concentrate increasing marginally..

The low variability within each suppressant type (mean coefficient of variation of all types ~10.8%, Table 3) indicates that this methodology is able to produce meaningful comparisons between suppressant mixes. However, the fact that there is some level of residual variability of results within a mix indicates that there remains a strong need for replication. The amount of replication required to obtain an accurate estimate of the mean volume of suppressant needed to fully extinguish the test fires can be estimated from the required margin of error, the selected statistical confidence level and the standard deviation of the mean volume of suppressant required [52]. More replication is required when the standard deviation of the required suppressant volume is high. For a margin of error of 0.1 l and a 95% confidence level, the required number of replicates for determining differences in raw volume (Table 3) is estimated be seven for water and foam and two for the two gel suppressants.

The relative performance of suppressants can be used to make comparisons between their effectiveness, with the most effective being those that require the lowest volume to extinguish the standard fires. The granular concentrate gel performed best in the examples presented here (Fig. 6), followed by the liquid concentrate gel, water and then foam. The example suppressants were found to be all statistically significantly different from each other ($p < 0.05$, Student's T-test, given the limited sample sizes), except for water and liquid concentrate gel with the normalised volumes (Fig. 6b).

Foam required the greatest volume of all of the suppressants used here and also had the greatest variability (Table 3). This result is probably because the foam tended to disperse more in the wind than the other suppressants (Table 1). This dispersal would have caused it to have a reduced coverage level (volume/area) over the flaming zone. The dispersal of foam in the wind has also been observed in the field during direct attack aerial suppression drops on head fires [37] and is likely to increase with concentration as more air can be mixed into the falling suppressant. In contrast to this, the gel suppressants tended to fall in a more cohesive line and provided a more efficient coverage over the flaming zone.

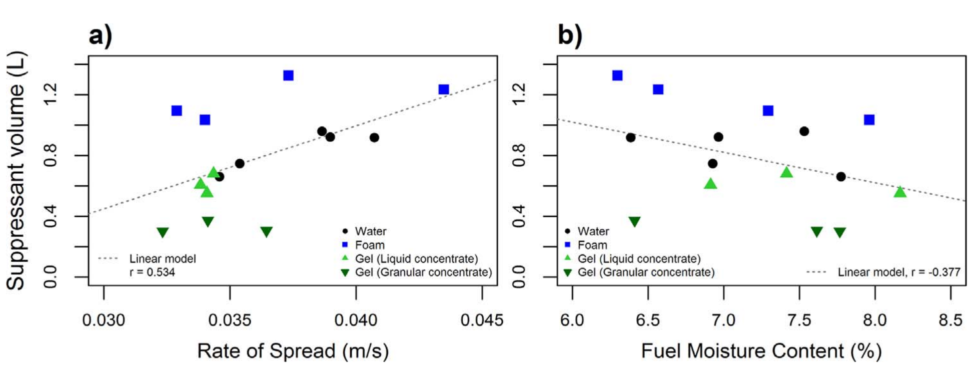


**Fig. 5.** Plots showing the relationship of a) rate of spread and b) fuel moisture content with suppressant volumes required for extinction.

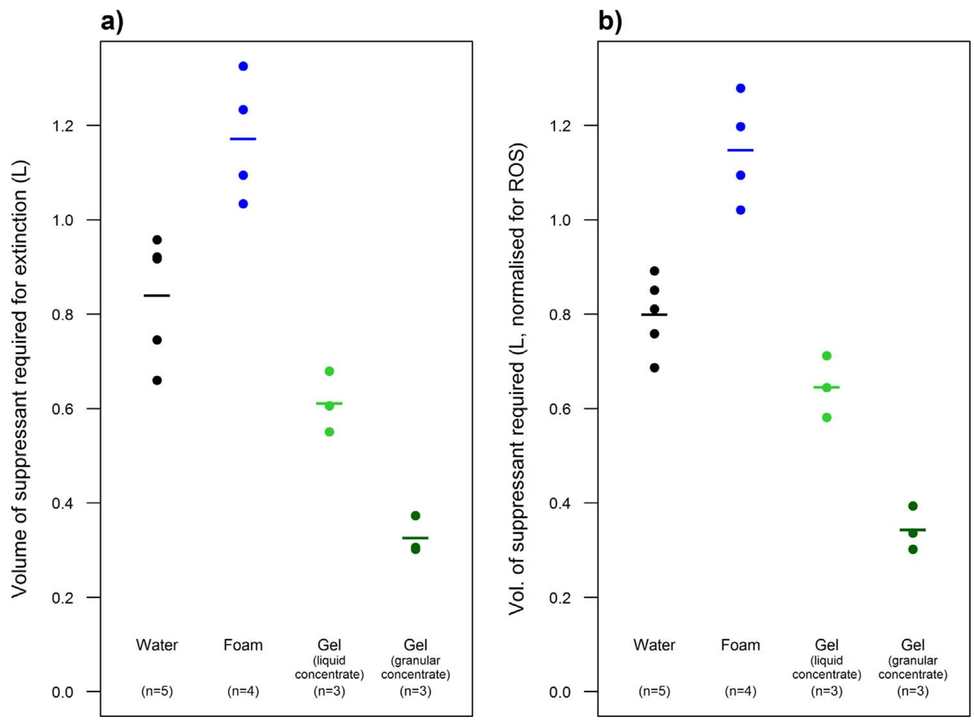


**Fig. 6.** Plots showing the distribution of the volume of suppressant required for extinction for the different suppressant types tested (points) for both raw volume (a) and volume normalised for rate of spread (ROS) (b). The horizontal bars indicate the mean volume for each suppressant type. Following normalisation, the mean and spread of volume of suppressant for water and foam was reduced, and remained unaltered or slightly increased for the gels.

**Table 3**
Summary of suppressant volumes (l) required for flame extinction for each suppressant type.

| | Water | Foam | Gel (liquid concentrate) | Gel (granular concentrate) |
|---|---|---|---|---|
| Raw volume | | | | |
| Mean | 0.840 | 1.171 | 0.611 | 0.326 |
| Standard deviation | 0.130 | 0.132 | 0.065 | 0.040 |
| Coefficient of variation (%) | 15.5 | 11.3 | 10.6 | 12.3 |
| Minimum | 0.659 | 1.034 | 0.550 | 0.301 |
| Maximum | 0.957 | 1.325 | 0.679 | 0.372 |
| Volume normalised for rate of spread | | | | |
| Mean | 0.799 | 1.147 | 0.645 | 0.343 |
| Standard deviation | 0.080 | 0.113 | 0.065 | 0.046 |
| Coefficient of variation (%) | 10.0 | 9.9 | 10.1 | 13.4 |
| Minimum | 0.686 | 1.021 | 0.581 | 0.301 |
| Maximum | 0.891 | 1.278 | 0.711 | 0.393 |

## 6. Discussion

This paper has presented a methodology that can be used to quantitatively compare the direct suppression performance of wildfire suppressants in a laboratory environment using natural fuels. The results from the example evaluation tests show that repeated experiments conducted with the same suppressants have low variability, with the results from each of the suppressants tested being mostly distinctive from the others. The results also show that the volume of suppressant required is affected by the fire's spread rate, which is influenced by the moisture content of the fuels under a constant wind speed and fuel load. Conducting replicate tests with the same suppressant mix and normalising the volume used by the ratio of the mean rate of spread to the observed rate of spread can be used to mitigate the effects of this variability in the suppressant volume used.

The suppressants used here were only trialled at a single concentration for the purpose of demonstrating the evaluation methodology and therefore the results do not fully reflect their potential effectiveness of the suppressants which may change with concentration. Applying this method to quantify suppressant performance at a range of concentrations would provide a useful basis to develop more costeffective protocols for their application in the field, particularly if some suppressants are shown to perform well at lower concentrations. The methodology presented here can provide the framework for testing a variety of suppressants at different concentrations and could also be used to assess the suppression performance of fire retardants when applied directly onto flames.

The subjective judgement of the operator in regard to the application of suppressant provides a potential source of unquantifiable error in this methodology, with the potential release of more suppressant than is required to extinguish a fire. This could occur if the operator does not make adequate assessments of residual flaming activity after each suppressant application. It is for this reason that suppressant application was done in short bursts with an intervening assessment period. The over-application of suppressants is more likely to occur when semi-suppressed flame fronts become discontinuous because the suppressant application impacts the full width of the fuel bed, not just the sections of residual flaming. Coarse fuel fragments and crushed fuel particles were removed from the litter during fuel preparation in order to reduce the likelihood of flame fronts becoming fragmented, as it is these components that are more likely to continue burning following the initial knockdown of flames. Test fires in fuels that have not had crushed particles removed are have more variation in their behaviour [40,47].

The conditions for the methodology presented here (i.e. wind speed, fuel moisture and fuel type and load) were selected to represent suppressant application on wildfires in Australian eucalypt forests during the summer months when there is high fire danger [48]. These conditions can be modified to represent other fire environments through the use of different fuel types, wind speed settings or fuel moisture conditions. The selection of a FMC closer to the equilibrium moisture content for the ambient conditions would minimise variability, but may prevent wildfire conditions being represented unless tests are able to be scheduled during very dry and hot weather (i.e. those conditions generally associated with wildfires) or the facility can be modified to control for temperature and humidity.

There are few published field observations of aerially-applied suppressants and none that have been able to conduct replicate drops in comparable conditions. This is because the variety of conditions experienced in the field, even within discrete locations and periods (e.g. weather conditions, fuel structure and continuity, terrain and fire behaviour), make it almost impossible to achieve adequate uniformity for comparing drop effectiveness [37]. As a result, findings from the methodology presented here cannot readily be validated at this scale. Fine-scale measurements of the size, spread and deposition characteristics of droplets from suppressant mixes applied in the field and laboratory could be used to determine how closely this methodology represents field application and to inform further development and refinement of the methodology so that it is able to represent field application as closely as possible. This would ensure that results from this applied method are relevant to the operational application of suppressants.

While the methodology presented here provides a means for comparing wildfire suppressants based on their effectiveness during direct attack, there are a range of other properties and qualities that are considered by fire agencies when selecting suppressants. These include cost, human and environmental toxicology, ease of storage, transport, preparation and application and holding time. Of these, holding time - the time between the application of suppressant and the fire actively spreading again in the affected area [37] - also provides a measure of suppression effectiveness. While holding time is of secondary importance to direct attack effectiveness, it provides a complementary temporal measure of effectiveness that is important in situations where there is potential for re-ignition from residual burning in coarse fuels or when there is a delay between aerial suppression drops and ground suppression. Assessments of holding time would need to be investigated separately as they require repeated ignition attempts of suppressant coated fuels with standard environmental conditions, suppressant treatment and ignition characteristics. Holding time assessments should also consider the ability of suppressants to penetrate fuel beds and the drying rates of these. There is a large range of potential combinations of these variables that could be investigated and the selection of these for the development of a standard comparative test should be designed to adequately represent field application conditions.

## 7. Conclusions

Suppressant enhancers are regularly used in direct attack roles during wildfire suppression and can be expensive to deliver, especially from aircraft. There is currently no standard method for evaluating or comparing the effectiveness of suppressant enhancers for extinguishing the flames on the propagating edges of wildfires. The methodology presented here provides a basis for testing and comparing wildfire suppressants in a repeatable and representative laboratory fire environment. The demonstration of the method shows that the fire behaviour and suppressant volumes used in repeated tests conducted with the same conditions have low variability and that the impact of small differences in fire behaviour can be moderated by normalising for rate of spread. This method can be applied to make direct comparisons between suppressant types and to investigate the effectiveness of different suppressant concentrations.

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