Fire Safety Journal 87 (2017) 71–79

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

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

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ARTICLE INFO

Keywords:
Firefighting
Bushfire
Direct attack
Aerial firefighting

ABSTRACT

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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http://dx.doi.org/10.1016/j.firesaf.2016.12.005
Received 27 April 2016; Received in revised form 27 November 2016; Accepted 3 December 2016
Available online 12 December 2016

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 ($< 0.9\ \mathrm{m\ s^{-1}}$). 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 $\mathrm{kW\ m^{-1}}$) 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