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Criteria and methodology for evaluating aerial wildfire suppression

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Abstract. Aircraft are often used to drop suppressants and retardants to assist wildfire containment. Drop effectiveness has rarely been measured due to the difficulties in collecting data from wildfires and running field experiments and the absence of definitions and measures. This paper presents a set of criteria and methodologies for evaluating the effectiveness of aerial suppression drops. These consider drop placement, coverage and effect on fire behaviour. This paper also details drop site and delivery conditions that are required for determining causal factors that influence drop effectiveness and allow drops to be compared. Examples of drop impact evaluations made during experimental fires are used to demonstrate these methodologies. The main methods proposed are based on the analysis of orthorectified airborne infrared imagery of drops, which can be used to measure drop dimensions, proximity to fire perimeter and their effect on fire spread. These evaluations can be used to compare tactics, suppressants and delivery systems and to inform cost–benefit analyses of aerial suppression.

Additional keywords: aerial firefighting, firefighting effectiveness, infrared airborne monitoring, retardants, suppressants.

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Introduction

Aircraft are used in a variety of wildfire management roles in many parts of the world. They can be used to deliver suppressants to sections of fire edge that are difficult to access on the ground and can reduce the intensity and spread rates to enable ground crews to work on sections of fire edge that may otherwise be unsafe (Plucinski *et al.* 2012). This is particularly beneficial during the initial attack of wildfires in remote locations (e.g. McCarthy *et al.* 2012). In most situations support from the ground is required to completely contain and extinguish fire edge (Plucinski *et al.* 2012).

Firefighting aircraft are used to deliver either retardants or suppressants. Retardants contain chemicals that inhibit flaming combustion by blocking key reaction pathways with the effect of reducing or stopping fire progression (Giménez *et al.* 2004), and are applied to fuels ahead of the fire in an indirect tactic. Suppressants, including water and water with additives such as foam surfactants, reduce combustion by removing heat from the reactants and are delivered directly onto the fire edge or immediately adjacent to it. The choice of tactics may depend on the availability of suitable aircraft, payload and airbase facilities for each option.

Aerial suppression is widely reported to be expensive (e.g. Ganewatta and Handmer 2009; Keating *et al.* 2012; Thompson *et al.* 2013) and requires considerable logistical support. Drop evaluations can be used to appraise operational tactics, thereby helping to determine cost effectiveness and enabling operational procedures to be more comprehensively evaluated. Databases containing information from multiple drop evaluations would provide a basis for comparing aircraft, delivery system types and fire suppression chemicals. For aerial suppression to be cost effective it is essential that drops are effective, although effective drops may not always be the most cost efficient means of wildfire suppression, such as when ground suppression resources can effectively complete the same suppression tasks at lower cost.

There are currently no published methods for evaluating the effectiveness of aerial suppression drops for wildfire suppression. The most common method for analysing drops has been cup grid tests, which use an array of containers placed in a grid pattern (Hodgson 1967; Suter 2000; Lovellette 2004) to compare drop ground patterns (drop footprint) from different aircraft, delivery systems and flight conditions. Cup grid tests are usually conducted in near calm conditions on clear flat sites, and therefore provide limited representation of drops made during wildfire conditions where wind, fire and vegetation influence the ground coverage pattern and reveal nothing on their effect on fire.

Table 1. Information on environmental and delivery conditions required for evaluating drop effectiveness

Category	Factors	Source data
Delivery aircraft	Flight conditions during drop (travel speed, height above ground, flight direction)	Recording GPS in delivery aircraft, analysis of imagery taken of aircraft
	Delivery system (load volume, system type and settings, flow rate, load viscosity)	Flight log records, flight crew interview, static drop test data, analysis of imagery, airbase records
Drop site	Vegetation or fuel (classification, height, canopy cover, fuel hazard, fuel moisture, heavy fuels)	Ground measurement
	Weather (Wind speed and direction, temperature, humidity, fire danger and drought indices)	Records from nearby weather stations, measurements made during ground measurement
	Terrain (slope and aspect)	Ground measurement, topographical data records
Fire behaviour	Part of fire (head, flank or backing), spread rate, flame dimensions, fuel consumption and intensity, spotting activity, burn and scorch heights	Analysis of airborne infrared imagery, observations during ground measurement, post-fire ground measurement
Ground suppression	Ground suppression activity in and around drop	Observations during ground or aerial measurement, interviews with firefighters

The effectiveness of retardants and suppressants has received a considerable amount of research in laboratory experiments (see reviews by Àgueda *et al.* (2008) and Giménez *et al.* (2004)); however, their aerial application for wildfire suppression has rarely been evaluated. This is probably because it is difficult to access and observe drop effects on wildfires (George 1990).

Cheney *et al.* (1982) and Plucinski (2010) evaluated drops during real and simulated wildfires using combinations of ground and infrared (IR) aerial observation methods. These studies highlighted the logistical difficulties in obtaining definitive evidence for evaluating aerial suppression drop effectiveness from wildfires but were still able to be used to inform agency resource selection decisions.

The Operational Retardant Effectiveness (ORE) program (George 1985, 1990) investigated the effectiveness of drops made on wildfires in the western United States. Observations were made from the air with IR cameras (George *et al.* 1989), and on the ground soon after. The ORE program developed guidelines for safe and effective retardant application (e.g. George and Johnson 1990) and coverage levels for different vegetation types (George 1985), and led to improvements in delivery systems (George and Fuchs 1991) and retardant rheological properties (George 2002).

Drops from a large air tanker were also investigated in Australia during Project Aquarius (Loane and Gould 1986). In this study, retardant drops on high intensity experimental fires in a dry eucalypt forest were monitored with an IR line scanning camera. These drops were found to have similar fire intensity limits to that of bulldozer-constructed fire breaks ($\sim$2.5–3 MW m^{-1}) for stopping fire progression. Numerous spot fires ignited fuels on the lee side of retardant drops when fires were more intense than this allowing the fires to spread past them, initially at a slower rate.

This paper is focussed on the effectiveness of aerial suppression drops. The specific objectives of this paper are to:

(i) Propose criteria and methods for quantitative evaluation of aerial suppression drops in terms of their effect on fire behaviour.
(ii) Demonstrate the evaluation methodology using examples from experimental fires.

Considerations for drop evaluations

This section discusses the information that is needed to characterise the environmental and drop delivery conditions associated with a drop and the information required to evaluate the effectiveness of drops.

Drop conditions

The environmental and delivery conditions associated with drops should be recorded to provide supportive contextual information to the evaluation. This information is essential when factors influencing drop performance are being investigated, or drops are being compared. Drop conditions can be grouped into four main categories relating to the delivery, drop site environment, fire behaviour and other forms of suppression (Table 1).

The delivery of the drop has a large influence on the coverage and shape of the drop footprint, particularly through the aircraft flight operation (e.g. height above ground, travel speed), the type and settings of the delivery system and viscosity of the payload (George and Blakely 1973; Swanson *et al.* 1975, 1978; George 1982, 1985; George and Johnson 1990; Amorim 2011*a*, 2011*b*). Environmental factors also affect drop footprints in a variety of ways. For example wind, particularly cross winds, cause drops to disperse, which can reduce coverage levels and potentially drift off target (George and Blakely 1973; Amorim 2011*a*, 2011*b*). Vegetation can intercept drops in effect lowering their coverage level (Calogine *et al.* 2007). As a result higher coverage levels have been recommended for fires in dense vegetation types (George 1985).

Environmental factors also influence fire behaviour (e.g. McArthur 1967; Pyne *et al.* 1996; Cruz *et al.* 2013), which subsequently affects the viability of drops. Drops are less likely to be effective when fire behaviour is intense (Loane and Gould 1986). The viability of drops can also be enhanced by the actions of ground-based suppression resources working in the same area (e.g. George 1990; Plucinski *et al.* 2007). In some cases, the combination of both resource types working together can allow the suppression of sections of fire edge, which may not have been possible with either resource type working alone (Plucinski *et al.* 2012).

Table 2. Questions for the evaluation of aerial suppression drops

Topic area	Number	Question
Objective	1	What was the objective of the drop?
	2	How was the drop to be executed to achieve the objective?
Placement	3	Where was the drop located relative to (a) the target, (b) the fire edge and (c) anchor points[A]?
Coverage	4	What were the (a) area, (b) length, (c) width, (d) orientation and (e) coverage quality of the drop footprint?
Effect on fire behaviour	5	What was the reduction in fire behaviour in terms of (a) short-term rate of spread and (b) flame height and (c) what was the effective drop length?
	6	Was the drop breached by (a) spotting, (b) burn around or (c) burn through, and if so how long did it hold?
Evaluation	7	Did the drop meet the stated objective?
	8	If the objective was not met, explain how and why?

[A]An advantageous location that provides a barrier to fire spread that is used for constructing a fireline to minimise its chance of being outflanked (NWCG 2011).

Drop evaluation

The evaluation of a drop requires characterisation against defined criteria that are relevant to the drop's objectives and the extent of the effect on fire behaviour to be measured, which are covered by the questions listed in Table 2.

The first two questions (Q1 and Q2) in Table 2 are concerned with drop objectives. Aerial suppression drop objectives focus on fire behaviour reduction, which can be expressed in terms of rate of fire spread and flame-related parameters, at a range of temporal and spatial scales and for a variety of reasons. The objective for a given drop, or tactic involving one or more drops, is normally set to fit into the overall suppression strategy for a fire and to be achievable for the expected environmental and resourcing conditions. Although individual drop objectives are rarely documented during wildfire suppression operations, they are usually communicated verbally when tactical decision makers request drops and typically identify a target location.

Drop objectives provide a clear starting point for evaluations (Q1) and should state the intended temporal and spatial extent of the drop. The temporal extent is the duration of the desired effect on fire behaviour, with the most extreme being to stop the fire edge from spreading beyond the drop by completely extinguishing it. More often drop objectives require a reduction in fire behaviour until ground suppression resources arrive or weather conditions moderate. The spatial extent intended for a drop may vary from being localised, focussing on the drop site and immediate surrounds, to a broad scale that considers the effects across large sections of the fire.

The drop objective information should also include some information about the tactics used (Q2). This should document the resources used to execute the drop and the instructions on how they were intended to be used, including the target area identified for the drop.

Questions three to six are concerned with the measurement of what happened during the drop and cover three major topic areas: placement, coverage and effect on fire behaviour.

Question three is concerned with the aspects of drop placement and considers location with respect to the intended target (Q3a), fire edge (Q3b) and anchor points (Q3c). An effective drop will affect the intended target (Q3a), which for a direct attack drop will be a section of fire edge (Q3b). Other drop targets include fuels ahead of the fire, including those in front of a structure requiring protection. Drops may be linked with other drops and anchor points (Q3c) when being applied as part of a line-building tactic. Drops used for other tactics, such as slowing fire progression, do necessitate anchoring. Linked drops typically have the same objective and can be evaluated as if they were one drop. The distance between the drop and intended target, fire edge and anchor points should be measured to quantify placement accuracy.

Question four is focussed on drop coverage in terms of the size, orientation and coverage quality of the drop footprint. The size of the drop footprint can be described in terms of the area (Q4a), length (Q4b) and width (Q4c) of ground fuels covered by the drop. Drop orientation (Q4d) accounts for the alignment of the drop footprint (axis along maximum drop length) with that of the target. A large variation between these can limit the length of drop affecting the fire edge. The orientation of a drop can be limited by wind direction and the availability of suitable flight paths, which can be restricted by terrain and other obstacles.

The quality of coverage within the drop footprint (Q4e) combines the coverage level (retardant or suppressant depth) and coverage consistency across the drop. Drops aiming to stop fires require higher coverage levels (in terms suppressant or retardant depth) than those aiming to slow fire progression. The level of coverage required to achieve an objective will also depend on fuel load, fire behaviour and availability of support from ground suppression resources. Higher coverage levels are required where there is dense vegetation, high intensity fire or delayed ground support. The quality of coverage can only be qualitatively assessed as it is not possible to measure the depth or gaps in coverage in the field; however, the relative effects of these for achieving the drop objective should be documented.

Questions five and six relate to the drop effects on fire behaviour and require comparisons of pre- and post-drop fire activity. An effective drop will stop or significantly slow the spread rate (Q5a) and reduce flame dimensions (Q5b) for a period that satisfies the objective, for example to stall spread until ground crews arrive. The effective drop length (Q5c) is the maximum length of fire edge continuously suppressed to the

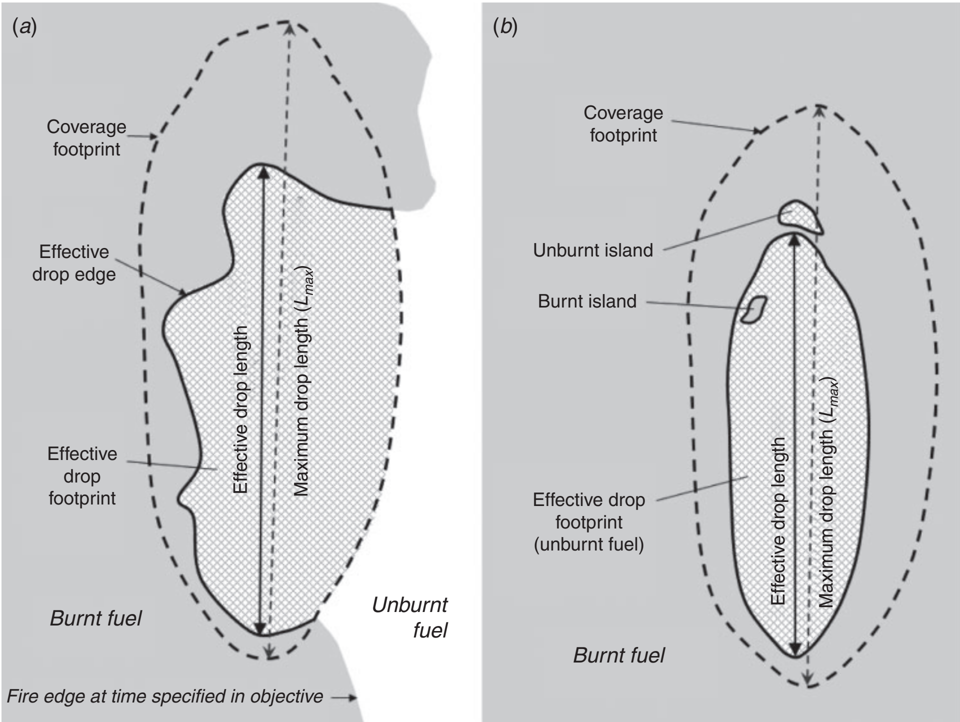

Fig. 1. Idealised plan of (*a*) an aerial suppression drop on the edge of a fire and (*b*) a drop that has been breached by fire.

required level (i.e. stopped or held until time specified in the drop objective) (Fig. 1). The effective length of drops that are breached by fire can be used to indicate the length of fire edge that could have been suppressed if it were not breached.

Question six refers to the three mechanisms that cause drops to be breached by fire: spotting, burn-around and burn-through. Spot-fire breaches (Q6a) occur when embers are lofted across drops and ignite fuels on the unburned down-wind side. Burn-around breaches (Q6b) occur when fire passes around the drop and can be a result of poor drop anchoring (Q3c). Burn-through breaches (Q6c) occur when fire passes over a drop and may be a result of poor coverage on the ground or suppressant drying. For a direct attack drop, holding time is the interval between the time of the drop and the time the fire passes over the far-side edge of the drop. For an indirectly applied drop it is the interval between the fire arriving at the near-side edge of the drop and passing over the far-side edge. Holding time provides a temporal measure of the drop effect and can be used to make comparisons between drops.

The final two questions summarise the drop outcome in terms of the objective in a simple binary answer (Q7) and provide an opportunity to document the reasons for a negative outcome (Q8). Negative drop outcomes should be explained in terms of the measured parameters (Q3–6), execution (Q2) and drop conditions.

Measurement methods

Evaluation of drop effectiveness requires the measurement of quantities listed in Tables 1 and 2. A range of suitable methods should be considered as some methods are often unavailable because of restricted site access or resource availability during critical periods. The most important methods are those that can be used to measure drop and fire conditions during the critical periods before, during and after their deployment.

Ground-based measurement

Ground-based drop measurement provides the best means for characterising site conditions (Table 1) although the amount and type of data that can be collected depends on timing and the type of suppression chemical used. Ground measurements made during and soon after direct attack drops, or when fires reach indirect attack drops, can provide very useful information as the interaction between the fire and the drop can be closely monitored and critical measurements can be made. However, safe access for on ground measurement may only be feasible when the fire behaviour is mild. Although sites are more accessible once the fire is extinguished the information is less accurate and more difficult to collect.

Wildfire behaviour observations can be used to determine flame dimensions and rate of spread (e.g.: Gill and Knight 1991; USDI National Park Service 2003) before and after a drop, or by making comparisons of similar sections of fire edge that have been treated with those that have not. Post-fire investigation techniques (e.g. Whight and Bradstock 1999) can be used to reconstruct fire behaviour in these situations.

The extent of drop coverage footprint (Fig. 1) cannot be determined from the ground unless drops contain a coloured dye. The effective drop footprint can easily be determined from the perimeter of burned and unburned fuels within the drop footprint (Fig. 1). Ground coverage levels have only been determined for retardant drops where the chemical contents of retardants coating litter at the interface of burnt and unburnt fuels can be analysed to determine the coverage level that caused the fire to stop (Van Meter *et al.* 1985).

Measurement of drop site conditions incorporating vegetation structure, fuel attributes and basic terrain conditions can be undertaken using standard field methods (e.g. USDI National Park Service 2003; Gould *et al.* 2007, 2011). Weather conditions can be estimated from observations from nearby meteorological stations.

Ground-based site measurements provide an opportunity to determine the role of other suppression resources in the area of interest. These should document the type of resources working in the area and the nature and timing of the work undertaken by them. Site maps identifying the drop footprint should include measurements of drop dimensions (Q4) and should identify features such as the drop target, fire edge and anchor points (Q3) and gaps in coverage.

Airborne imagery methods

Observations from independent aircraft and other vantage points are often the only reliable means of recording the immediate effects of drops on fire behaviour (e.g. Cheney *et al.* 1982; George 1990; Plucinski 2010). Ground-based vantage points, such as hill tops, usually provide imagery that is too oblique for applying orthorectifying techniques.

Infrared cameras mounted in aircraft allow drops and fires to be viewed through smoke and light tree canopies and have been recommended for monitoring aerial suppression drops in previous studies (e.g. George *et al.* 1989; George 1990; Ogilvie *et al.* 1995). Aircraft fitted with IR line scanning detectors designed for mapping fires (Matthews 1997) are also able to detect drops and can be used to capture a sequence of images for drop measurement (e.g. Biggs 2004).

Previous investigations of aerial suppression using IR imagery have been limited to analysis of the unprocessed imagery (George *et al.* 1989; Ogilvie *et al.* 1995; Biggs 2004; Plucinski 2010). Although unprocessed IR imagery can be used to determine drop hold times and the causal mechanisms of breaching (Q6), processing and analysing the imagery can provide accurate measurement of fire spread and the spatial extent of drops and their effects. IR imagery suitable for orthorectification and processing requires instrumentation that is properly located and configured. The monitoring platform should be located at a height that allows the fire perimeter section of interest to be captured in the field of view, while still providing adequate spatial resolution during the critical periods before and after drops being affected by fire. An IR camera using a band in which the flame signal is low (e.g. the thermal infrared band 8–12 μm or the near infrared band with an appropriate filter at 3.90 μm) will allow the advance of the fire front to be determined using the temperature edge value at the interface between embers and the background.

IR data processing requires multiple steps. The first step is the correction and spatial registration of IR images using a projective geometry multiple-view technique (Hartley and Zisserman 2003; Pastor *et al.* 2006). This step requires a minimum of four ground reference points of known coordinates. Following this, the location of the fire edge and the perimeter of the drop footprint can be defined in the orthorectified frames using a temperature threshold. Temperature differentials determined immediately after a drop reaches the ground can be used to define the perimeter of the detectable drop coverage footprint. The technical details of the IR imagery processing methods applied here are presented in detail in Pastor *et al.* (2010) and Pérez *et al.* (2011). The drop coverage footprint can be used to determine the dimensions and orientation of the drop (Q4), but cannot determine the variation in coverage level across the footprint in the presence of fire. Contours of multiple drops can be used to examine links between drops (Q3c) including their overlap length and combined dimensions.

A rate of spread (ROS) map containing fire spread isochrones and vectors (speed and direction) for every pixel within the fire area in the images (e.g. McRae *et al.* 2005; Planas *et al.* 2011*a*) can be produced from a sequence of fire perimeter frames. These can be used to identify sections of the fire (e.g. head, flank) based on geometric definitions (see Planas *et al.* 2011*a*, 2011*b*). Drop footprints can be superimposed on ROS maps to calculate the distance between an indirect drop and the fire, and the proportions of direct attack drop footprints affecting unburnt, burning and burnt fuels (Q3b). This analysis can be undertaken using appropriate IR temperature ranges for each characteristic zone (Pérez *et al.* 2011) and can also be used to calculate drop orientation (Q4d) using the difference between the bearing of the perpendicular to maximum drop length and the ROS vector for that part of the fire (perpendicular deviation). The greater the perpendicular deviation the shorter the section of the fire perimeter intercepted.

The reduction in fire activity resulting from a drop (Q5) can be measured in terms of ROS change. The percentage of the short-term (1 min) ROS reduction in the area of influence of the drop can be determined by comparing the mean ROS of the section of the fire front where the drop has been placed immediately before the drop with that determined over the following minute.

Delivery aircraft data

A range of instruments have been used to collect drop flight and delivery system data in the past (e.g. George 1982), however much of it can now be obtained using Global Positioning System (GPS) devices that record track files, with information on travel speed, flight direction and altitude, at frequent logging rates (≤1 s). GPS devices that are connected delivery systems can record the exact point when the payload was first released from the aircraft (Ault *et al.* 2012; Thomasson 2012). Alternatively, release time can be determined by cross-referencing the GPS track file with synchronised footage of the drop.

The volume of the payload is often less than the capacity of the delivery system (Trethewey 2007) and should be documented when available. Delivery system settings should also be recorded for systems with adjustable flow rates and release periods.

Examples from aerial suppression experiments

In this section we apply the methods previously presented to drops undertaken during field fire experiments. The experiments were conducted in Ngarkat Conservation Park, eastern South Australia in March 2008 (e.g. Plucinski *et al.* 2011).

Table 3. Environmental and delivery conditions associated with the example drops
n.a., not available

Drop reference:	G2	R2 and R3	F1	F4 and F6
Ignition date and time (hh:mm:ss[A])	3 March 2008 14:35:00	4 March 2008 15:51:12	5 March 2008 15:00:07	5 March 2008 15:00:07
Drop time (hh:mm:ss[A])	14:44:26	14:56:54 (R2), 15:04:23 (R3)	15:11:07	15:23:13 (F4), 15:33:09 (F6)
Time of impact with fire (hh:mm:ss[A])	14:44:28	15:57:42	15:11:10	15:23:16, 15:33:11
Air temperature[B] (°C)	35.4	31.5	37.1	36.0
Relative humidity[B] (%)	8	24	13	13.3
Wind speed[C] (km h^{-1}) mean	15.3	17.7	8.1	19.2
Gust	24.7	32.1	17.9	32.6
Forest Fire Danger Index[D]	44.2	23.7	33.4	41.5
Part of fire	Head	Head	Flank	Flank
Flame height (m)	2.0	3.8	n.a.	1.0
Rate of fire spread (m min^{-1})	40.2	42.6	34.8	5.8 (F4), 7.2 (F6)
Fireline intensity[E] (mean) (MW m^{-1})	6.9	5.0	4.8	0.8 (F4), 1.0 (F6)
Suppression chemical	Water enhancing gel (Thermogel 200 L[F])	Long-term retardant (Phoschek D75R[F])	Class A foam (Phoschek WD881[F])	Class A foam (Phoschek WD881[F])
Drop tactic	Direct attack	Indirect attack	Direct attack	Direct attack
Aircraft height above ground (m)	n.a.	n.a.	37	23, 12
Aircraft drop speed (m s^{-1})	n.a.	50	57.5	58.8, 56.4
Aircraft bearing (° true north)	n.a.	n.a.	157	41, 47

[A]Australian central standard daylight savings time (GMT + 10.5 h).
[B]Measured in a Stephenson's screen 1.5 m above the ground 0.5–1.3 km from the plots.
[C]Measured at 10 m above the ground in an open area 0.5–1.3 km from the plots.
[D]McArthur (1967).
[E]Byram (1959).
[F]The use of trade names is for information and convenience to the reader and does not constitute endorsement or approval by the authors or affiliated institutions.

Experimental fires were conducted in three large plots (52–93 ha) with suppression only provided by aircraft. The plots contained 22 year old mallee-heath fuels and had a mean fuel load of 0.46 (±0.05) kg m^{-2} (Cruz *et al.* 2010, 2013).

Each plot was burnt on a different day, with a different type of fire suppression chemical (gel, long-term retardant and foam). All drops were delivered by a single engine air tanker (Airtractor AT-802F, with longitudinal drop doors fitted). Each drop comprised of a full load (3000 L) that was delivered with the drop doors fully opened. The drops in the gel and foam plots were made directly onto the fire edge. The first drops were delivered soon after the fire had burned through a grid of fire behaviour instrumentation, and subsequent drops were made at intervals of ~10 min. The objective of each of these drops was to stall the section of the fire edge that was spreading the fastest at the time of the drop for the 10 min until a follow up drop was made. The retardant drops were made in the path of the fire before ignition. These drops were laid in an 'L' shape so that the head fire would reach one section and a flank fire would reach the other. The objective of the retardant drops was to stop the section of fire that reached them from spreading further.

The experimental fires were filmed from a helicopter with a standard video camera (visual spectrum) and an IR camera (AGEMA Thermovision 570-Pro, FSI-FLIR Systems, operating in the 7.5–13-μm range equipped with a frame grabber storing sequences of 240 × 320-pixel images). The helicopter was positioned so that the majority of the plot was in view for the duration of each fire, allowing for fire behaviour and drops to be recorded and monitored (e.g. Pastor *et al.* 2010). Drums containing burning wood were used as hot reference points.

Most ground-based drop site measurements could only be made post-fire as fire intensity was too high to allow safe access during the burns. Weather measurements were made using an automatic weather station located 1.3 km from the furthest plot.

Drop evaluation examples

Four examples were used to demonstrate drop evaluations. They comprise a gel drop released over a head fire (G2), two linked retardant drops (R2 and R3) laid before a head fire and three foam drops (one single (F1), two linked (F4 and F6)) used for direct attack on a flank fire (which was the fastest part of the fire at the time of the drops due to the headfire reaching the end of

Table 4. Objectives, measured characteristics, and evaluation outcomes of the example drops in terms of the evaluation questions listed in Table 2
n.a., not available

Question:	G2	R2 and R3	F1	F4 and F6
1) Drop objective	Stall the section of the fire edge that was spreading the fastest at the time of the drop for 10 min	Stop the head fire	Stall the section of the fire edge that was spreading the fastest at the time of the drop for 10 min	Stall the section of the fire edge that was spreading the fastest at the time of the drop for 10 min
2) How executed?	Direct attack using a single full load of gel delivered by an AT-802F	Linked drops delivered by two AT-802Fs in the path of the fire before ignition	Direct attack using a single full load of foam delivered by an AT-802F	Direct attack using a two full loads of foam linked together delivered by two AT-802Fs
3a) Intended target	Head fire	Head fire path	Left flank	Left flank
Actual location	Head fire	Head fire path	Left flank, mostly inside fire perimeter	Left flank
3b) Burning area (%)	n.a.	0	82	1 (F4), 6 (F6)
Burnt area (%)	n.a.	0	14	53 (F4), 30 (F6)
Unburnt area (%)	n.a.	100	4	46 (F4), 64 (F6)
3c) Linkage	Not linked	R2 and R3 linked together, R2 poorly linked to other drops	Not linked	Well linked
Overlap length (m)	–	n.a.	–	42
4a) Surface area (m^2)	n.a.	5814[A]	3555	10 971
4b) Maximum drop length (m)	n.a.	240	137	276
4c) Mean width (m)	n.a.	26.0	31.4	39.8
4d) Perpendicular deviation (°)	n.a.	0	15	30 (F4), 19 (F6)
Appropriate orientation	Yes	Yes	Yes	Yes
4e) Adequate coverage of fuels?	Yes (in centre)	Yes other than link at western end	n.a. (misplaced)	Yes
5a) 1 min Rate of spread reduction ($m\,min^{-1}$ (%))	n.a.	0 (100%)	0.23 (40%)	0 (100%)
5b) Flame height reduction (m (%))	1.8 (90%)	3.8 (100%)	n.a.	1.0 (100%)
5c) Effective drop length (m)	15	191	0	90
6a) Breached by spotting?	Yes, held for 6:23 min	No	Yes, before drop	No
6b) Breached by burn around?	Yes, in 11:42 min	Yes, in 6:37 min	Yes, in 2:30 min	Yes, after 47:06 (F4) and 37:12 (F6) min
6c) Breached by burn through?	Not in centre section of drop	In the far western edge after 7:14 min	Yes, after burn around	Eventually, after burn around
7) Objective met?	No	No	No	Yes, held for more than 30 min
8) Reason(s) for not meeting objective	Breached by spotting in 6:23 min	Poor anchoring allowed fire to burn through poorly linked section	Drop misplaced and breached by spotting before delivery	–

[A]A low estimate as it was measured 45 min after the drop when much of the drop would have dried.

the plot). The linked drops were considered together as they had the same objective. The environmental and delivery conditions of the example drops are presented in Table 3 and the objectives, measured characteristics and evaluation outcomes are given in Table 4.

The first example drop (G2) was an unanchored gel drop that was placed directly on a fast spreading (40.2 $m\,min^{-1}$) head fire to slow fire progression. This drop was observed from the ground during the fire and surveyed afterwards. The drop was filmed with the airborne IR camera; however, full imagery analysis was not possible due to the inability to detect reference points and orthorectify the frames. This prevented the measurement of many drop characteristics and effects (as indicated by the cells marked 'n.a.' within the column for drop G2 in Table 4). Ground observations found that flame heights reduced from 2.0 to 0.2 m in the centre of this drop. The drop was breached by a spotfire within 6.5 min of application and was burned around within 12 min. The drop footprint was eventually burnt by

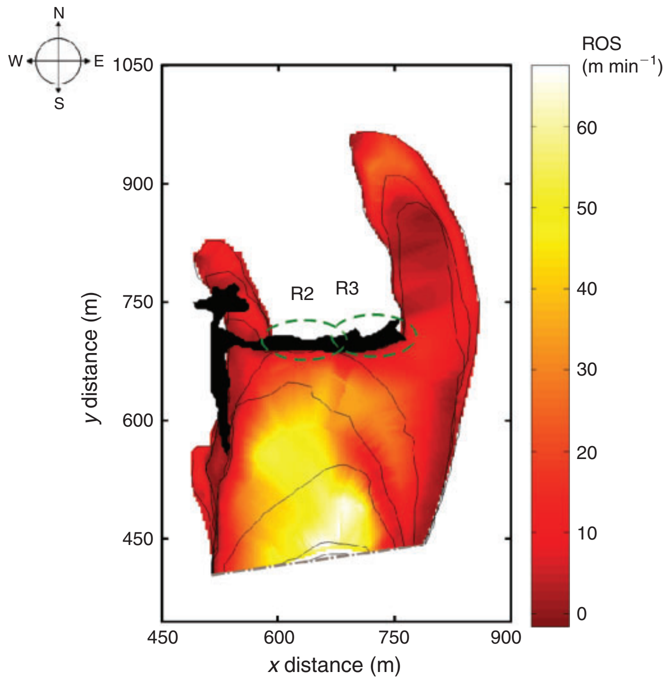

Fig. 2. ROS map for the fire in the plot with the retardant drops. The isochrones show the fire extent at 30 s, 1 min, 2 min, 5 min, 7 min, 14:30 min; 16:00 min, 18:00 min and 19:30 min. The black shadow shows the drop area, which was determined from orthorectified airborne infrared imagery captured immediately before ignition (45 min after they were applied). The dashed black line shows the ignition line.

backing fire after IR recording had stopped and the suppressant had dried other than a 15 m-long section. Although the drop did have the effect of slowing the fire, this effect was short lived and the drop did not meet its specified objectives.

The second example comprises two linked retardant drops (R2 and R3) laid 1 h before an intense (0.5 MW m^{-1}) headfire reached them. These drops stopped the forward spread of the fire but were burnt around on the eastern side 6.6 min later. The fire burned through a section on the western end linking to other drops that was only lightly covered in retardant (Fig. 2). The fire spread at less than 0.1 m s^{-1} when burning through this section. These drops left an unburnt island that had an effective length of 191 m. These drops would have stopped the fire had they been adequately anchored to fuel breaks or other high coverage retardant drops.

The third example is of foam drop (F1) made on the forward edge of an active flank of a fast moving fire (Fig. 3). Nearly all of this drop (96%) fell on burning and burnt fuels (see Pérez *et al.* (2011)). A spot fire that could be seen in the infrared footage was ahead of this drop when it was laid. The drop was completely burnt around within 2.5 min and only reduced the rate of spread by 40% in the first minute. It had very little effect on the spread of this fire, as shown by the fact that all fuels within the drop footprint area were burnt. Ground observers were unable to get close enough to estimate flame dimensions.

The final example is of two linked foam drops (F4 and F6) that were made on a less intense section of the same flank as F1 (Fig. 3). These drops held the fire for 37 min before being burnt around and met the objective of slowing the fire. The overlap between these drops was 42 m and the overall length of the

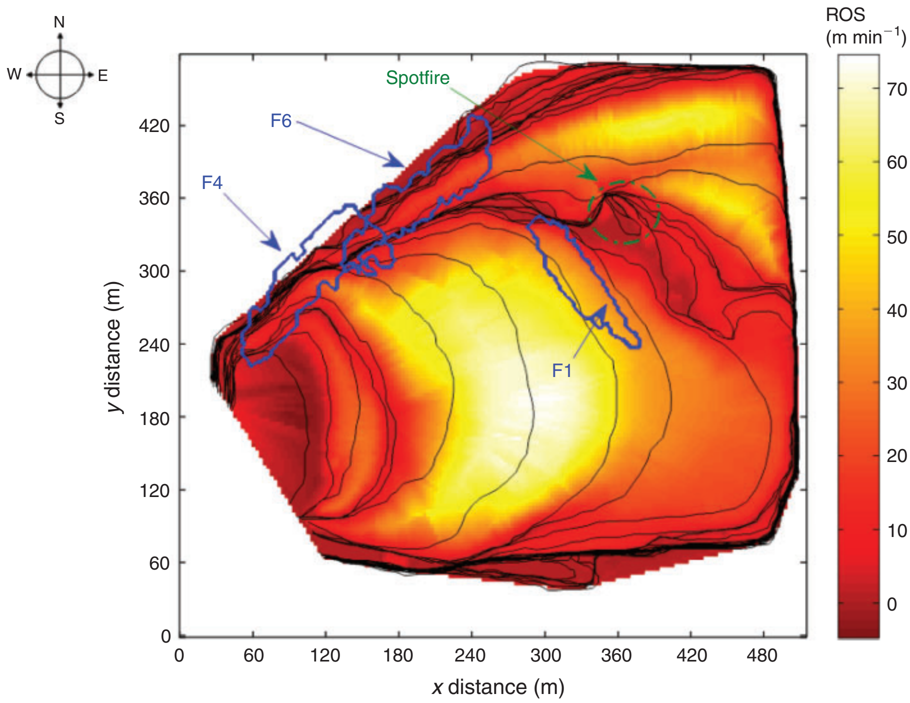

Fig. 3. ROS map of fire in the plot used for foam drops. The black lines are the isochrones drawn every minute. The drop perimeters (blue) were determined from orthorectified airborne infrared imagery captured immediately after they were applied.

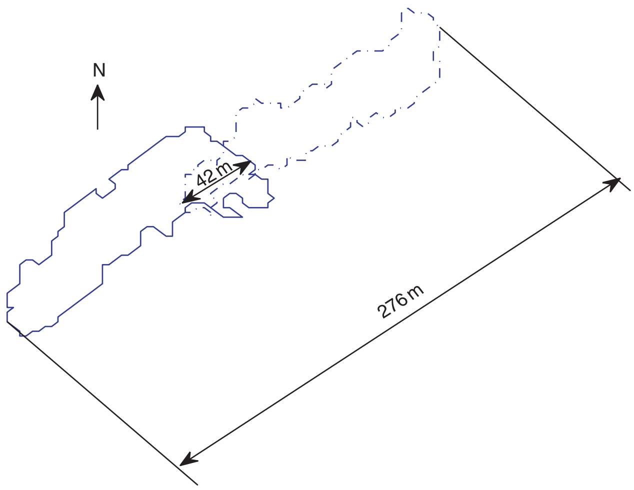

Fig. 4. Drop outlines of F6 (dashed line) and F4 (solid line) determined from orthorectified airborne infrared imagery captured immediately after each was applied.

combined drop coverage footprints was 276 m (Fig. 4). Elevated fuels remained unburnt along a 90-m section of these drops, although eventually most of the litter fuels burned.

Discussion

This paper has presented criteria and methods for evaluating the effectiveness of aerial suppression drops on reducing fire behaviour and measuring the extent of those effects. One of the major lessons learned from the experimental fires was that IR imagery captured from independent observation aircraft provides the best known means for monitoring and recording the interactions between fire and aerial suppression drops. Although previous studies have advocated the use of airborne IR imagery (George *et al.* 1989; George 1990; Ogilvie *et al.* 1995), we have also shown that processed imagery can be used to measure fire spread, drop dimensions and thus the effects that drops have on fire behaviour.

The other major lesson learned from the experimental fires was the primary importance of drop placement for the success of aerial suppression drops (Plucinski *et al.* 2011). Drops that are misplaced (e.g. F1) or poorly positioned (e.g. those that are not anchored) have a limited effect on slowing fire spread. The retardant drops (R2 & R3) used as examples here demonstrate the importance of effective positioning, as it is likely that they would have stopped the fire had they been adequately anchored to other drops or fuel breaks at each end because they stopped the most intense part of this fire before the flanks of the fire burned around them (Fig. 2).

Although the drop evaluation examples provided here demonstrate the feasibility of the methods, they are limited in their scope. First they come from fires burning in one open canopy vegetation type. More work is required to investigate the feasibility of airborne IR analysis methods in vegetation with a thicker canopy.

The other major limitation of the examples is that they all come from pre-planned experimental fires where fuels were comprehensively assessed and reference points were established before ignition. Applying these methods during wildfires will be more challenging due to their unplanned and chaotic nature and the lack of opportunities to establish reference points and appraise the unburnt site. Newer IR systems with coupled visible and IR cameras can use distinguishing landscape features as reference points. Some newer IR camera systems are able to orthorectify imagery in real time and do not need reference points. These camera systems would be more suitable for use on wildfires, though may still require ground verification of reference points.

The methods presented here could readily be applied to evaluate drops made on fires providing that airborne infrared imagery can be sourced and orthorectified, and sites can be surveyed on the ground. In the absence of either of these data sources efforts to undertake evaluations can still address many of the evaluation criteria (Table 2) and obtain much of the contextual environmental and delivery information and make a valuable contribution for demonstrating the effectiveness of aerial suppression and identifying where improvements can be made. Considerable effort is required to ensure that quality data is captured during the critical periods of the evaluation. This data can then be processed and analysed at a later time.

The ability to undertake quantitative aerial suppression evaluations will become easier and more widespread as developing technologies such as advanced IR monitoring systems, aircraft tracking systems and unmanned aerial vehicles become available to fire suppression agencies. Future work in this field needs to first test the feasibility of undertaking airborne IR drop evaluations during wildfire suppression operations and adapt it for use in a range of vegetation types. Following this the method should be used to develop a dataset of drops made in a variety of conditions. This dataset could be analysed to determine the factors influencing drop effectiveness in operational conditions and to compare tactics, aircraft, delivery systems and suppression chemicals. The results of these analyses would provide evidence for refined operational procedures.

Conclusions

Aircraft are regularly used for wildfire suppression but their effectiveness has rarely been evaluated. The criteria and methodology presented and demonstrated here provide a basis for undertaking quantitative evaluations of aerial suppression drops and demonstrate the immense value of orthorectified airborne IR imagery for determining the spatial and temporal extent of drops and the effects that they have on fire behaviour. Further work is required to test these methods on wildfires and in a variety of vegetation types.

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