Review of aerial suppression effectiveness research literature

Prepared for the Natural Hazards Research Australia project *Why fly? How do we know that aerial firefighting operations are effective and efficient*

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We acknowledge the Traditional Custodians across all the lands on which we live and work, and we pay our respects to Elders both past, present and emerging. We recognise that these lands and waters have always been places of teaching, research and learning.

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Cover: Type 2 (medium) helicopter dropping on a grassfire in Ascot Victoria 2018, photo Wayne Rigg AFSM, Country Fire Authority

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Executive summary

Aircraft are an important and costly component of bushfire suppression operations. Most decisions related to the application of aircraft at bushfires are based on anecdotal experience as there is little quantitative data and knowledge of how they are used and how effective they are in the Australian context, particularly for large fires. The Natural Hazards Research Australia and CSIRO *Why fly? How do we know that aerial firefighting operations are effective and efficient?* project was established to address these concerns and is a focussing on aircraft that drop retardants and suppressants. This literature review has been undertaken to document the pertinent research relevant to the *Why fly?* project.

The most significant research projects on aerial suppression have been undertaken in the United States (US), with a wide range of related topics studied over many decades. The largest, and most relevant study to the *Why fly?* project is the recent Aerial Firefighting Use and Effectiveness (AFUE) conducted by the Department of Agriculture. The AFUE study compiled a dataset with 27,611 operational drops and developed a novel methodology comparing drop outcomes against objectives. The only report published for this study presents general patterns of aircraft use, performance and effectiveness for different aircraft types. The AFUE study found that the most common drop objectives were delaying fire spread and reducing fire intensity, which are difficult to assess objectively due to their indefinite nature. The report also revealed that eleven per cent of the drops examined did not interact with fire and that most drops occurred at large fires, an observation recorded in other recent US studies.

Other large studies of aerial suppression effectiveness include the Operational Retardant Effectiveness (ORE) program undertaken by the US Forest Service and Project Aquarius undertaken by CSIRO. Both were undertaken in the 1980s and provide few details of methodologies or observations. The ORE program aimed to determine the quantity of retardant required for different types of fire but was unable to achieve this goal due to the complexities of operational data collection. Recommendations from the ORE program were used to improve aircraft delivery systems, retardant properties and operational procedures. Project Aquarius used airtanker drops on experimental fires to estimate fire behaviour thresholds for effective drops on fires in dry eucalypt forests, with results feeding into a cost benefit study to inform fleet composition. Other smaller studies have mostly involved just a few observations of drops during experimental fires and bushfires, that have often been used to assess the suitability of a particular aircraft for a firefighting role and to provide case studies of notable incidents.

While several aerial suppression effectiveness research projects have been undertaken in Australia, these have been considerably smaller than AFUE and ORE with limited numbers of observations that were limited by the technology available when they were undertaken. There have been no previous studies of aircraft use on Australian bushfires, other than a scoping study that presented some isolated examples demonstrating that aircraft tracking and event data are of great benefit for such research. Results from studies undertaken in other countries are likely to have limited applicability in Australia owing to differences in tactical application, fire behaviour, vegetation, terrain, weather and water availability.

The research discussed in this review has used a variety of data collection methods to assess aircraft use, drop effectiveness and the conditions affecting them. Aircraft tracking and event data is emerging as an important new data source for analyses of operational responses to fires and has only been used in a few studies to date. However, this data source can only provide some of the information required for analysable case studies of firefighting aircraft, with other sources such as agency records, interviews with key personnel and imagery and videography captured during operations required to provide critical information on suppression objectives, fire behaviour, environmental conditions and supporting suppression responses.

1) Introduction

The use of aircraft for suppressing unplanned bushfires has become more common over recent decades, including within Australia, which has seen significant increases in the number and size of firefighting aircraft. Public opinions on aerial firefighting effectiveness are largely based on media portrayals and observations of actions made during the heat of bushfire emergencies when the focus is on limiting the impacts of fire and there is no time for clear contemplation. Operational perceptions of suppression effectiveness are also anecdotal, based on personal experience and as a result difficult to compile. There is a clear need for empirical data to provide evidence of when aircraft are and are not capable of making valuable contributions to bushfire operations.

The recent *Royal Commission into National Natural Disaster Arrangements* (Binskin et al. 2020) recommended (Recommendation 8.2) that research and evaluation into aerial firefighting be undertaken to assess the specific aerial suppression capability needs of states and territories and to explore the most effective aerial firefighting strategies. The Commonwealth Government has expressed support for this and other critical research into bushfires and natural hazards as well as a desire for a full and evidence-based understanding of the capability required to support decisions on the future of aerial firefighting and to deliver an operationally effective fleet that is scalable, adaptive and cost efficient (Department of the Prime Minister and Cabinet 2020). The *2021-2026 National Aerial Firefighting Strategy* also endorses this recommendation and other related research for informing aerial firefighting (NAFC 2021). State inquiries into the 2019-20 fire season have likewise highlighted a need for more evaluation and knowledge of existing aerial firefighting resources (Inspector-General for Emergency Management 2020) and have recommended that the composition of aerial firefighting fleets be reviewed (Owens and O'Kane 2020).

The *Why fly?* project, funded by Natural Hazards Research Australia, has been developed to help address these concerns. This new project aims to describe the current Australian aircraft use profile and to evaluate the effectiveness of aerial firefighting. While there are many other operational uses of fire management aircraft, such as reconnaissance, supervision, transport, intelligence gathering and aerial ignition, the *Why fly?* project is focused on the use of aircraft in ’bombing’ roles, defined as the delivery of liquid payloads, such as water, foam, gel and retardant, onto the burning edges of fires, or fuels in the path of fires with the aim of suppressing fires and protecting values at risk.

This literature review is focussed on research that is directly related to that being undertaken in the *Why fly?* project. Many topics associated with aerial suppression have not been covered, such as drop footprint quantification (e.g. George and Blakely 1973; Suter 2000; Lovellette 2004), retardant and suppressant characterisation (e.g. Giménez et al. 2004; Àgueda et al. 2008; Plucinski et al. 2017), environmental impacts of retardants and suppressants (e.g. Song et al. 2014; Lanctôt et al. 2024; Puglis and Iacchetta 2024), influences of drops on micro-meteorology and aircraft (e.g. Wheatley et al. 2023), delivery system performance (e.g. George and Johnson 1990; George 1992; Refai and Hsieh 2022) and physics-based energy balance models for suppressant drop impacts on combustion (e.g. McFayden et al. 2023).

The initial research component of the *Why fly?* project is a use study that will examine how different aircraft are assigned under different conditions and for different objectives, while the main component will examine aerial suppression effectiveness, particularly through the attainment of suppression objectives. Discussions of previous research into aircraft use and the effectiveness of aerial suppression drops are presented in sections 2 and 3. The *Why fly?* project presents an opportunity to utilise aircraft tracking data to support this research, with previous research on this topic presented in section 4. Finally, a summary of use and effectiveness studies in the context of the *Why fly?* project is presented in a concluding discussion (section 5).

1.1) Background

Bushfire suppression effectiveness is a difficult subject to study and quantify as it is influenced by many diverse variables (Plucinski 2019a). In this context, the term 'effective' is used for actions that generate desirable fire outcomes (Thompson et al. 2017). From an operational perspective, effective actions can be defined as those that meet pre-defined objectives (Plucinski and Pastor 2013). The availability of, and difficulty in collecting impartial and reliable operational bushfire suppression data has been a major limitation for research (Thompson et al. 2013; Calkin et al. 2014b; Stonesifer et al. 2015; Stonesifer et al. 2016; Plucinski 2019a; Simpson et al. 2021) and much of the existing operational knowledge of suppression effectiveness is anecdotal, highly personal and difficult to compile.

A recent review (Plucinski 2019b, 2019a) of bushfire suppression effectiveness research classified previous studies by the scale of their investigation, identifying four discrete scales: flames, firelines, incidents and landscapes (Table 1). The fireline and incident scales are most relevant to the *Why fly*? project as they are concerned with the impact that suppression has on fire behaviour and on incident outcomes. There have only been limited studies at these scales (covered in section 3) and they are essential for examining suppression resource types and tactics on suppression outcomes, and the influence of weather, fuel, terrain and fire behaviour variables on them.

Scale	Description
Flames	Small fires confined within organised fuel beds, usually in controlled laboratory conditions. These have mostly been used to study wildfire suppression chemicals.
Fireline	Sections of fires (experimental fires and wildfires) engaged by suppression resources. These have mostly focussed on the effect of suppression actions on fire behaviour and the productivity of suppression resources.
Incident	Case studies of bushfire incidents (of a variety of sizes). These have examined suppression efforts on fire outcomes. They are usually qualitative due to limitations in data availability and have also examined suppression effects on fire behaviour and resource productivity.
Landscape	Studies of multiple fires across large areas and longer time periods (years, decades) to investigate basic incident outcomes related to fire size and containment time with most focussed on initial attack successes.

TABLE 1 DESCRIPTIONS OF SUPPRESSION RESEARCH UNDERTAKEN AT DIFFERENT SCALES (PLUCINSKI 2019A, 2019B)

A significant proportion of the previous research on the effectiveness of aerial suppression has focussed on their benefits during initial attack (e.g. McCarthy 2003; Plucinski et al. 2007; Plucinski 2012; Plucinski et al. 2012; Plucinski 2013; Collins et al. 2018; Wheatley et al. 2022b). Studying suppression success during initial attack is relatively straight forward as the objective of the incident and supporting suppression actions is to contain a new fire start (Stonesifer et al. 2021). These initial attack studies have found that the use of aircraft can increase the probability of successful containment of initiating fires, particularly when they are deployed quickly, during more challenging conditions, such as on dry and windy days, or on fires that are in remote locations. They have also recognised that not all fires require aircraft in a successful suppression response and that some fires, burning during severe conditions, will escape containment efforts regardless of the resources sent to them (Plucinski et al. 2012; Calkin et al. 2014a; Katuwal et al. 2018; Wheatley et al. 2022a). However, these studies are limited in that they have not been able to investigate finer details influencing individual drops, such as fire behaviour, fuels and ground suppression support.

Suppression effectiveness on fires that have escaped initial attack is much more complex because there are many potential objectives for suppression and there are often multiple concurrent tactics and objectives (Thompson 2013; Plucinski 2019b; Stonesifer et al. 2021). As a result, there has been far less research on the use and effectiveness of suppression resources, including aircraft, on larger fires with studies being limited to small numbers of observations and specific locations and weather conditions. More details on these studies are discussed in sections 2 and 3.

2) Aircraft use research

Understanding how aircraft are used during bushfire suppression operations is critical to understanding their effectiveness and provides a solid basis for promoting their effective utilisation (Stonesifer *et al.* 2015; Stonesifer *et al.* 2021). Aircraft use studies also allow the comparison of usage patterns with intended use profiles and conditions where they are considered to be effective (Stonesifer *et al.* 2016).

There are many potential variables associated with aircraft drops that can be investigated by cross referencing the times and locations of drops with other data sources. Table 2 provides an overview of these with explanations of their use and examples from previous research, where it exists. Nearly all previous studies of aircraft use have been undertaken by the US Forest Service, with many focused on large airtankers, as this aircraft type has had more available data. Many of these studies have examined aircraft use as a proxy for aircraft effectiveness due to the absence of direct drop observations (Thompson et al. 2018; Stonesifer et al. 2021). Many of these US studies have found that aircraft are more frequently used on larger fires, in contrast to the policies of the agencies that operate them who aim to prioritise initial attack (Thompson et al. 2013; Calkin et al. 2014b; Stonesifer et al. 2015; Stonesifer et al. 2016; USDA 2020).

Variable(s)	**Description and rationale**	**Findings from previous studies**
Fire size	The size of fires at the times that drops are made has been used to examine the types of fires that aircraft have been assigned to, mostly the proportion of initial attack fires.	US studies have found that airtankers tend to be used more during large (>42 ha) fires, despite the primary intended use being the initial attack (Thompson et al. 2013; Calkin et al. 2014b; Stonesifer et al. 2015; Stonesifer et al. 2016). The AFUE study found this use to be more typical of large helicopters, scoopers and large airtankers than small helicopters and airtankers (USDA 2020).
Time since fire reported and fire status	Linking drop times with incident timing records, such as fire report time (an estimate of ignition time) can also provide information initial attack use and the speed of the response. Linking drop timing with fire status (going, contained, under control etc.) can provide further information on the stages of suppression aircraft are being used.	Not covered in previous studies.
Vegetation (including type, fuel load and age)	Vegetation type has previously been used as a proxy for probability of success, with drops in denser vegetation (e.g. forests) assumed to be less effective than those in open vegetation types (Thompson et al. 2018). Linking drop locations with fuel load or age could help to determine if these influence drop placement decisions.	Stonesifer et al. (2016) and Thompson et al. (2018) found large airtanker drops were more commonly used on fires in forest vegetation from a selection of US wildfires. Fuel load and age have not been investigated in previous studies.
Terrain and terrain features including proximity to water sources	Slope steepness has been used as a proxy for probability of success, with drops on fires on steeper slopes assumed to be less effective than those on fires in flatter areas because of differences in fire behaviour (Thompson et al. 2018). Distance from water sources may influence the type of aircraft used and the placement of helicopter drops.	Stonesifer et al. (2016) and Thompson et al. (2018) found large airtankers were more commonly used on steep slopes from a selection of US wildfires.
Presence of ground crews	Determining whether drops are supported by ground crews is likely to influence objectives and outcomes. Collecting this information cannot be readily automated, so requires more effort to collect than other variables.	Most airtanker drops (84%) observed in the AFUE study were supported by ground crews and were more commonly undertaken to delay fire spread, than drops that were not supported by ground crews.
Time of day	Time of day has been used as a proxy for probability of success, with drops undertaken during peak burning periods of the afternoon, assumed to be less effective due to assumed elevated fire danger and behaviour (Thompson et al. 2018).	Stonesifer et al. (2016) and Thompson et al. (2018) found large airtanker drops were more common in the afternoon than at other times from selections of US wildfires. Reinke et al. (2021) show that aerial suppression drops from five large case study fires from the Australian 2019/20 season tended to be most frequent during the

Variable(s)	**Description and rationale**	**Findings from previous studies**
		late afternoons.
Weather conditions	Weather conditions, expressed through a fire danger index, has been used to approximate fire behaviour. Specific aspects of weather, such as wind speed and temperature that affect aircraft performance could be investigated.	Simpson et al. (2022) compared the distributions of daytime Forest Fire Danger Index with that for four large fires that burned during the 2019/20 fires season in NSW and found drops were more common during more extreme burning conditions.
Part of the fire, fire behaviour and fire severity	The part of the fire perimeter being suppressed (head, flank, backing) can be linked with fireline intensity and are also associated with wind direction with respects to drops. Linking drop locations with post-fire severity maps could also indicate the influence of fire behaviour on drop placement.	Not found in any previous study
Drop contents, volume and coverage level	The contents (typically, water, foam, gel or retardant), volumes and coverage levels of aerial suppression drops have a large influence on tactical options and effectiveness. Records of these can provide information on tactics.	Operational evaluations of large airtanker use during trial periods undertaken by NAFC (2015) who reported that 80% of drops were full loads, most drops were made at high coverage levels (>2.4 mm (Coverage level 6)) and all were retardant. A later trial of other large and very large airtankers (NAFC 2017) also reported some sorties that used gel for direct attack (34/ 146) in Australia during the 2015/16 and 2016/17 seasons, which may reflect differing preferences in another state.
Flight conditions	Air speed and height above ground at the time of dropping (Stonesifer et al. 2016) can be investigated to determine if drops are being made in the recommended ranges for specific aircraft types. This could also be used to investigate the influence of other variables, such as vegetation and terrain on dropping conditions	George (1990) reported that maximum drop speeds listed in some aircraft type certificates were frequently exceeded during fire suppression operations in the US during the 1980s. Stonesifer et al. (2016) later found that drop airspeeds and heights were generally within the recommended ranges and above safety ceilings.
Objectives	Linking drops with their intended outcomes is critical for assessing their effectiveness. Data on objectives is essential for providing information on intended tactical uses for aircraft in different situations when with other variables and for different aircraft types.	Delaying fire spread was the most common drop objective (40 %) for all drops in the AFUE study (USDA 2020), with helicopters and scoopers also used to reduce fire intensity and airtankers most likely used to halt fires advance.
Proximity to values at risk	The proximity of drops to values at risk from fires, such as houses, can provide estimates of the proportion of drops used for protective roles and indicate how the presence of built structures influences suppression tactics.	Stonesifer et al. (2016) found that most drops in the US were delivered near the rural-urban interface, while many were made near highways and some were placed in remote areas.

TABLE 2 VARIABLES THAT CAN BE INVESTIGATED IN AERIAL FIREFIGHTING USE STUDIES WITH EXAMPLES FROM PREVIOUS STUDIES

The only project that has specifically examined the use of different aircraft types is the Aerial Firefighting Use and Effectiveness (AFUE) study (USDA 2020). This major study compared objectives for 27,611 drops from different aircraft types used on 270 fires across the US between 2015 and 2018. The only report that is currently available for this project (USDA 2020) presents some high-level results showing that drops are used for a wide variety of reasons beyond line building, which had been assumed to have been the main objective for use prior to the study. The AFUE project categorised drop objectives into six groups (Table 3) and compared their incidence for different aircraft. The vast majority (69 per cent) of drop data collected was from helicopters and for responses to large fires. The AFUE study found that the most common objective for drops was to delay fire spread (40 per cent of all drops), while reducing fire intensity was a common objective for helicopters (~40 per cent) and water scooping aircraft (~35 per cent) and halting fire spread was a common objective for other fixed wing airtankers (~45 per cent). Extinguishing fire was an uncommon objective, typically 3 per cent of drops or less, except for Type 3 helicopters (17 per cent) and multiengine scoopers (9 per cent). Components of the AFUE project related to the effectiveness of drops are discussed in section 3.1.

Drop objective	Description
Reduce fire intensity/flame length	Drops undertaken to cool an area of fire activity. This may allow ground personnel to work closer to the fire or be used to reduce burning into crowns and limit ember generation.
Delay fire spread/retard growth	Drops made with the intent of delaying the arrival of fires or slowing the growth of the fire. Examples include buying time for ground resources to construct line or for evacuations.
Support ignition operations	Drops undertaken to support ignition (back burning) operations on wildfires. Examples include wetting areas to reduce spotting potential, keeping fire in check to ensure implementation of preplanned ignition operation, or reducing growth potential in the event of spots to prevent escape, etc.
Point protection	Drops made to protect values at risk (vulnerable points, including property and sensitive environments). These are generally undertaken within the immediate area of the value at risk or to reduce the probability of fire reaching the value at risk or to reduce damage to the it.
Line fire/halt advance	Drops undertaken to construct aerial fireline to halt fire spread. These drops are used to halt the spread of a section of the fire's edge before, during, or after ground engagement or without the aid of ground personnel.
Extinguish fire/spot fire	Drops aiming to fully extinguish the entire portion of the fire or spot fires (generally a rare occasion, usually a small area, and likely in fine fuels).

TABLE 3 DROP OBJECTIVE CATEGORIES USED IN THE AERIAL FIREFIGHTING USE AND EFFECTIVENESS PROJECT (USDA 2020)

Understanding aircraft use during large fire events will benefit incident management teams by allowing them to keep track of aircraft use and determine if it aligns with incident objectives. Stonesifer et al. (2021) proposed a range of analytical tools to summarise aircraft used during large incidents to inform incident management teams of aircraft use within incidents. These depict aircraft use by type and with regards to the time of day, terrain, vegetation type and fire danger (weather). They are often presented as maps indicating drop locations in relation to fire perimeters and potential fire control locations. These tools build an earlier proposal for an Aviation Exposure Index designed to estimate risk exposure to aviation accidents (Stonesifer et al. 2014). This Aviation Exposure Index is calculated daily for incidents from the number and type of aircraft assigned, flight times and long-term accident rates and is designed to help guide fire managers in balancing trade-offs between attaining wildfire management objectives and reducing the exposure of individuals engaged in aerial firefighting activities.

The only Australian study that has included aspects of aircraft use is the preliminary examination of aircraft tracking data undertaken by Simpson et al. (2022) for the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC). This work presented examples of aircraft use during the 2019/20 "Black Summer" fire season in NSW to demonstrate the utility of aircraft event data (drops and fills). They provided examples of drop distributions at large fire events for fire weather, indicated using the Forest Fire Danger Index, and distance to houses, comparing these distributions for distributions for the whole fire. While the scale of these examples was limited, they demonstrated immense potential for aircraft tracking and event data for providing information on aircraft use within fire events.

The Why Fly project aims to undertake assessments of how aircraft, deployed in bombing roles, are currently used in Australia, including how different aircraft types are used for different objectives and in different conditions and will use similar aircraft event data to that used by Simpson et al. (2022). More information on the use of tracking data for bushfire suppression research is provided in section 4.

3) Aerial suppression effectiveness research

This section considers research that has investigated the effectiveness of drops that have interacted, or were intended to interact, with fire. This includes field-based studies and studies using novel data sources, such as tracking and remotely sensed data, and investigations of drops made during unplanned wildfires and planned experimental fires. Major projects and groups of related projects are discussed in sections 3.1 to 3.4, while other smaller studies, and current projects, are summarised in in section 3.5.

3.1) USDA Aerial Firefighting Use and Effectiveness study

The Aerial Firefighting Use and Effectiveness (AFUE) study (USDA 2020) is the most relevant and recent project investigating drop effectiveness. It was given the mission of systematically documenting the operational utilisation and tactical contribution of aerial firefighting resources in support of incident objectives (USDA 2020). AFUE was the largest study of aerial firefighting study in terms of its total budget ($US11M (Gabbert 2021)) and the number of drops analysed. A total of 18,929 helicopter drops, 3,303 scooper drops, and 5,379 airtanker retardant drops were investigated across 272 incidents in the US between 2015-2018. There is currently only one report presenting some overall results for this project (USDA 2020), while a website (USDA No date) and online video (NWCG 2018) contain some further information about the methodologies.

Field observations of drops and their effects on fires were made from the ground and surveillance aircraft during wildfires by four trained, strategically located three-person crews dedicated to the project (NWCG 2018). These teams were tasked with collecting pertinent data without impacting suppression operations, including mapping aerial drop activity, documenting environmental conditions, recording incident and drop objectives and assessing outcomes for aerial suppression drops. The fires sampled included a high representation of large fires in areas that were more accessible for the observation crews. Drops were analysed based on concise standardised categorical lists of objectives (Table 3) and outcomes (Table 4). Performance evaluation was agnostic as to why and how objectives were selected, or what values were protected.

Drop outcome	Description
Unknown/no data	Observers were unable to evaluate the drop outcome (e.g. due to safety, access, smoke, fire behaviour, etc.) and know that the drop(s) interacted with the fire.
No fire interaction	The drop did not interact with wildfire (i.e. fire did not reach retardant drops).
Burned through, spotted over, outflanked, change in tactics/priorities, failed to contribute	The drop failed to contribute due to fire advancing past the drop by burning across (through) the resource actions, by means of firebrand ignition, by burning around (outflanking) the end of the resource action, or the drops did not have a chance to contribute to broader task outcomes due to a change in tactics/priority.
Reduced fire intensity	The drop successfully reduced fire intensity in the portion of the fire with which it interacted enough to contribute to successfully meeting objectives without committing more resources.
Protected point(s) successfully	The drop successfully prevented interaction or damage to the object of point protection
Delayed fire spread	Fire advanced past the drop(s), but the delay was enough to contribute to the successfully meeting planning area objectives without committing more resources.
Halted fire spread	The drop(s) successfully stopped the portion of the fire it interacted with from advancing.

TABLE 4 DESCRIPTIONS OF DROP OUTCOMES USED WITHIN THE AFUE STUDY (USDA 2020) TO DETERMINE DROP EFFECTIVENESS WHEN COMPARED TO OBJECTIVES (TABLE 3)

The AFUE report (USDA 2020) used two performance metrics to summarise patterns in results across the study. The first, interaction percentage, quantified the proportion of drops that interacted with fire. This is the number of drops with known outcomes that interacted with the main fire divided by the total number of drops with known outcomes. Eleven per cent of all the drops observed during the AFUE study did not interact with fire. These are likely to be mostly retardant drops placed ahead of fires as contingency lines acting as backup containment lines in case primary containment lines closer to fires were breached. Interaction percentages were highest (close to 100 per cent) for light helicopters and scoopers, which are only used in direct attack roles, and were lowest for airtankers (80 per cent for SEATs, and ~75 per cent for LATs and VLATs), which are more likely to apply retardant indirectly.

The second main performance metric used was the probability of success (PoS), which was calculated as the number of effective drops divided by the total number of drops with known and interacting outcomes. Effective drops were those that were observed to have met or exceeded their objective. PoS can be compared for drops undertaken in any conditions to investigate how success varies with factors such as drop objectives, aircraft type, and fire type (categorised size). The AFUE report presents some PoS comparisons for different aircraft types and different drop objectives but does not investigate the influence of other variables, such as those related to vegetation, terrain, weather and fire behaviour, even though the data collected would be suitable for this.

The PoS for all observed drops that interacted with fire during the project was 0.82. This figure tended to be higher for helicopters (0.74 to 0.88) and scoopers (0.72 to 0.90) than it was airtankers (0.67 to 0.74). The objectives of point protection and line halt/line advance (Table 3) had the lowest PoS for light (Type 3) and medium (Type 2) helicopters (~0.15-0.45) and single engine scoopers (~0.15-0.40). Point protection had the highest PoS for airtankers (~0.78-0.87) and heavy (Type 1) helicopters (~0.70). Most aircraft types were found to have lower PoS during extended attack fires (escaped initial attack, but not large in area), presumably because these fires generally present more challenging fire behaviour and suppression conditions.

The majority of AFUE drops were reported to have had the objectives of delaying fire spread (41 per cent of all drops), reducing fire intensity (32-48 per cent of helicopters and scoopers) or halting fire spread (41-45 per cent of airtanker drops). While most of these drops were classified as having high PoS, the objectives are vague and unable to be quantified. Later work by Stonesifer *et al.* (2021) has recommended that objectives be more specific so that they can be properly assessed with regards to what gains they might deliver for the broader suppression effort. This would require some articulation of how much of a delay or pause in fire spread, or reduction in intensity, is required to benefit overall objectives.

The AFUE study was reported to have been shut down in 2021 (Gabbert 2021) and no publications have been released since the 2020 report. The data collected during the AFUE project is the most extensive and comprehensive ever collected on aerial suppression and could provide many more insights into how firefighting aircraft are used and where they are most likely to be effective than has so far been reported.

3.2) US Forest Service Operational Retardant Effectiveness Program

Prior to the AFUE study, the US Forest Service had undertaken a similar project, the Operational Retardant Effectiveness (ORE) program in the 1980s (George 1985; 1990). This project had the objective of determining ‘how much chemical or retardant is needed to do a given fire suppression job?’, collecting data from 2763 drops, which were mostly retardant applied by fixed wing airtankers on wildfires (George 1990; George 1992). Airtankers were instrumented to quantify retardant release characteristics and dedicated observers, who were also independent of firefighting operations, monitored drops from helicopters fitted with infrared cameras

(George et al. 1989) and from the ground. There are very few details of the field methodologies or evaluation data other than some information on flight and delivery system conditions (George and Fuchs 1991). The ORE program was unable to fully address its' main objective due to operational and environmental complexities (USDA Forest Service 1990), however it led to improvements in aircraft delivery systems (George and Fuchs 1991), retardant rheological properties (George 2002), and contributed to safe fire aviation operations through the development of the *Ten principles of retardant application* (George et al. 1989), which became a best practices field reference (Stonesifer et al. 2016).

3.3) Project Aquarius and related 1980s Australian research

Aerial suppression studies were also undertaken in Australia in the 1980s by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) with the assessment of drops from some large airtankers. A project assessing drops from a modified military aircraft on Victorian bushfires during one fire season (Cheney et al. 1982) was conducted during the 1982 Victorian fire season prior to Project Aquarius, a multi-objective experimental field study of firefighter health, bushfire behaviour and control techniques (Budd et al. 1997b). Project Aquarius field experiments included observations of airtankers on high intensity experimental fires that were undertaken to feed into a cost benefit analysis of airtankers for Victoria (Loane and Gould 1986).

Cheney et al. (1982) evaluated drops from a C-130 Hercules fitted with a pressurised retardant delivery system used on four bushfires in Victoria in 1982. Despite considerable efforts to reach incidents, they were only able to make a few direct observations while fires were still burning. They found that the airtanker drops did not reduce the area burned or containment time of the only fire burning during elevated fire danger conditions. They did however report that drops appeared to assist in the suppression of fires burning during moderate conditions, though also noted that less expensive resources could have been used to achieve the same effect. The study advised that trials limited to opportunistic observations made during bushfire operations cannot be guaranteed to provide sufficient evidence for making sound decisions about the role of airtankers.

The effectiveness of retardant drops from a large airtanker (DC6) on experimental fires representative of bushfires was investigated during the field component of Project Aquarius to feed into an aerial suppression cost benefit study for Victoria (Loane and Gould 1986). Retardant drops were made on high-intensity (up to 7500 kW m^{-1}) experimental fires in a dry eucalypt forest and were monitored with an aerial infrared line scanning camera. The specific experimental methods and results of the aerial suppression component of the project were not formally published, however the major findings are discussed in Loane and Gould (1986) and some general project methodologies were described by Budd *et al.* (1997a).

The most significant finding from the aerial suppression component of Project Aquarius was that retardant drops were able to hold fires up to an hour when the fireline intensity was less than 2000 kW/m. Drops were overcome by spotting when impacted by fires that were more intense. Loane and Gould (1986) estimated that this value could be increased to 3000 kW/m when ground crews could follow up within an hour and also reported that drops on fires up to 5000 kW/m could sometimes reduce intensity to levels that would allow ground crews to access affected firelines. These fireline intensity limits are similar to those that they estimated for dozer-constructed firebreaks and are considerably higher than those estimated for firefighters with hand tools (1000 kW/m (Budd *et al.* 1997a)) during this project. Fireline intensity thresholds have provided guidance for operational planning, informed categorisation within the new Australian Fire Danger Rating system (Hollis *et al.* 2024) and have been applied in research predicting climate change impacts on future fire extents (Wotton *et al.* 2017).

3.4) Bushfire CRC suppression projects

A project funded by the Bushfire Cooperative Research Centre (Bushfire CRC) investigating aerial suppression effectiveness motivated by the high use and cost of aircraft during some busy fire seasons in the early 2000s was mostly focussed on a strategic level operations study developing initial attack success models (e.g. Plucinski et al. 2007; Plucinski 2012; Plucinski et al. 2012; Plucinski 2013). This project also included some case studies of fires (Cruz and Plucinski 2007; McCarthy et al. 2012) and observations of aerial suppression drops made at bushfires (Plucinski et al. 2007) and experimental fires (Plucinski et al. 2006; Plucinski et al. 2011; Plucinski and Pastor 2013).

That project had difficulty making observations at busfires, mostly due to the time taken to travel to fires being longer than the time aircraft were working on them. The research team tried to make comparisons of fire intensity indicators (burn and scorch heights) in drop areas before, during and after fires but were only able to access 16 fires (26 drops) in three years, with only three of these accessed while aerial suppression was still underway. Most of the drops they observed were retardant as they could not reliably identify uncoloured suppressant drops in the field. They found that drops were much more likely to effectively hold fire growth when ground suppression could access them within two hours (Plucinski 2010a). This project later abandoned field data collection due to the inevitability of not being able to attain a dataset suitable for analysis (Plucinski 2010a).

This project undertook field experiments in 2005 and 2008. The first involved water and foam drops from a medium helicopter on mild stubble fires in Tasmania. All of these fires (up to 4000 kW/m) were easily suppressed (Plucinski et al. 2006). The 2008 experiment was undertaken with high intensity fires in semi-arid mallee heath fuels in South Australia during very high fire danger conditions (Forest Fire Danger Index (McArthur 1967) 23-44, temperature 31-37 °C, relative humidity 8-24 per cent, wind speed 10-27 km/h) (Pérez et al. 2011; Plucinski et al. 2011; Plucinski and Pastor 2013) as part of a larger investigation of fire behaviour in this fuel type (Cruz et al. 2010). Three different fire suppression chemicals (gel, foam and retardant) were each applied to a fire in a large plot (52-93 ha) using two single engine airtankers (Airtractor AT-802F), with 27 drops assessed using orthorectified airborne infrared imagery (Pérez et al. 2011; Plucinski et al. 2011). The researchers found that they could not directly compare different suppression chemicals used because of differences in weather, fire behaviour and flight conditions between drops. However, the data collected demonstrated the importance of drop coverage, drop accuracy and drop placement and was used to develop evaluation methods and criteria for aerial suppression drops (Plucinski and Pastor 2013).

A field evaluation of a very large airtanker (DC-10) was later undertaken to help determine the suitability of this resource for use in Victoria (Plucinski 2010b). Evaluation drops were made on three trial fires following a lack of suitable bushfires to deploy the aircraft to. These drops were overcome by moderately intense (3200 – 6700 kW/m) head fires because of fire easily burning through gaps in drops in stubble fuels and by short distance spotting at a low intensity prescribed fire in a eucalypt forest. The evaluation report (Plucinski 2010b) recommended that the airtanker not be used in Australia due to these problems stemming from gaps in its drop footprints.

3.5) Other smaller projects and current research

There have been many small projects that have included aspects of field investigations of aerial suppression. These include experimental trials (Stechishen 1976; Newstead and Alexander 1983; Lu et al. 2023), observations of drops at bushfires (Ault et al. 2012a; Center of Excellence for Advanced Technology Aerial Firefighting 2020), and evaluations made using spatial data and interviews with firefighters (NAFC 2015; McKern and Patterson 2019) and are summarised in Table 5.

Projects and references	Methods and details	Findings
Early Canadian study of retardant penetration in forests (Stechishen 1976)	Retardant (Fire-Trol 931) dropped from a small airtanker (990 l Otter) onto fires small (30 x 30 m) experimental plots in coniferous (jack pine) forest in White River, Ontario, Canada.	Only a few plots were able to be burned. They observed that indirect retardant drops can stop low intensity surface fires where there is no spotting.
FPInnovations first field assessments of gel drops (Ault et al. 2012a)	Observed two helicopter gel drops on a moderately intense wildfire in a lodgepole pine forest in Manning, Alberta, Canada.	Found the drops were unable to stop the fire but did reduce the intensity to a level that allowed researchers to approach the area. They noted many challenges in making observations related to access, time limitations, safety and researcher availability.
NAFC evaluation of next generation large airtankers contracted to Victoria (NAFC 2015)	Retardant drops from two large air tankers (C130Q and Avro RJ85) made during 87 sorties were studied during the 2014/15 fire season across 4 Australian states. Evaluations of drop characteristics and effects on fire spread were made from post-incident interviews with key fire operations personnel and drop locations were mapped with final fire areas.	Most drops were reported to have been made at high coverage levels (≥2.4 mm (CL6)), found to penetrate forest canopies well and achieve their intended objectives. Post fire interviews for assessing drop effectiveness were open to subjectivity but were the only method available.
Country Fire Authority aircraft impact on small fires (McKern and Patterson 2019)	The effect that firefighting aircraft (mostly single engine airtankers) had on reducing the impact of six single-day Victorian fires was observed during the 2018-19 fire season. The perimeters of fires that had been suppressed with aircraft were compared with predicted fire extents for the same fires without aircraft, over similar timeframes to determine the benefit of drops for fire containment.	This work was mostly undertaken to develop an assessment methodology, which was found to be suitable for simple single day fires, but not for fires that burned for multiple days.
Colorado Center of Excellence for Advanced Technology Aerial Firefighting (2020) field comparison of gel suppressant drops	Drops containing three different water-enhancing gels (FireIce 561, BlazeTamer 380 and Thermo-Gel 200L) made by single engine airtankers directly on wildfires were assessed in Oregon and Washington in the US. Two dedicated observers travelled to fires to assess drops. They found it challenging to access fires, particularly due to a lack of wildfires in their intended study area, but still managed to collect data from many drops from other areas.	Gel drops were observed to be effective when quickly backed up by ground resources. Direct gel drops were reportedly more effective than water and foam drops and found to have longer holding times. However dense canopies limited penetration to ground fuels.
BNHCRC investigation of frequent satellite imagery to examine suppression activity (Reinke et al. 2021)	Used 10-minute interval imagery from the Himawari-8 satellite to examine the effects of aerial suppression during the 2019/20 fires in southeast Australia. They compared infrared brightness in cells with lots of aerial suppression drops with nearby reference areas with no aerial suppression.	The coarse spatial resolution of the imagery (two-kilometre pixels) limited the ability of the assessment of aerial suppression, as did the inability to account for other suppression or drop objectives.
BNHCRC investigation of aircraft tracking data for research (Simpson et al. 2022)	Conducted some example evaluations of aerial suppression effectiveness using tracking data and interviews with personnel involved in the suppression using data from the 2019/20 fire season in NSW.	Demonstrated that aircraft tracking and event data is well suited for assessing aerial suppression effectiveness when combined with other data sources, including information on drop objectives.
Chinese testing of helicopter drops for protecting power infrastructure (Lu et al. 2023)	Investigated water, foam and retardant drops from a light helicopter on experimental wooden crib fires in China. The static fire behaviour and coarse fuels are not representative of bushfires.	All drops were found to reduce flaming of the wooden cribs, with retardant being the most effective.
US Pacific Northwest National Laboratory retardant mapping from satellite imagery (Tagestad et al. 2023)	A methodology for mapping retardant lines and fires using satellite imagery was developed. Five large fires with prominent retardant lines from southwestern US were used to train the model and a further two were used to test it.	The purpose of this paper was to develop a methodology that quickly maps the full areal extent retardant drops. It does not contain any evaluation of the drops, but the method can be used to compare drop locations with the final fire extents.

TABLE 5 BRIEF SUMMARIES OF SMALLER AERIAL SUPPRESSION EFFECTIVENESS STUDIES

There are currently two projects underway that are of high relevance to the Why Fly project. Firstly, the Ontario Ministry of Natural Resources have planned to make detailed observations of drops from scooping aircraft (CL-415) remote boreal forest fires (Wheatley et al. 2024). The researchers plan to assess effectiveness by comparing fire behaviour and conditions before and after drops and to determine drop holding times using visual and infrared observations from surveillance aircraft and have drops applied on unsuppressed fires in a variety of formations to refine operational tactics.

Secondly, researchers from Colorado State University are currently undertaking a project to determine the effectiveness of large airtankers suppressing wildfire growth and identify conditions where they are most effective at slowing fire spread. They are applying economic modelling techniques to high-resolution spatiotemporal data of drops from tracking systems and satellite data of fire growth from fires from western US states and making comparisons between areas ahead of and behind retardant drops with nearby similar areas that were not protected by drops.

4) Applications of resource tracking and event data

Resource tracking and event data are relatively new data sources with great potential for supporting operational suppression research when combined with other data describing environmental conditions (Plucinski 2019b) and will be an important data source for the Why Fly project. Tracking and event data provides precise position and timing information, at regular intervals or for specific actions of interest respectively. For firefighting aircraft events of interest include loading aircraft and starting and ending drops (NAFC 2023). This data also has many operational uses related to safety, providing fire ground intelligence and supporting contracting. As this data is collected passively, it does not influence suppression actions in a way that might occur when observers collect data in the field.

Resource tracking studies, using systems such as Additional Telemetry Units (ATU's), have been undertaken using a range of suppression resource types for a variety of reasons including predicting travel times on escape routes for hand crews (Sullivan et al. 2020) and determining productivity rates of ground tankers (Butler et al. 2022; McCarthy et al. 2022). Most studies that have used tracking data have considered aircraft. These are summarised in Table 6.

Projects and references	**Data, resource type and application**	**Findings and application for project**
Bushfire CRC suppression project (Plucinski et al. 2007)	This study provided some early examples of tracks from GPS's mounted in aircraft which were matched to mapped drop footprints and fire edges and used to determine aircraft turnaround times.	Bushfire CRC aerial firefighting project (Plucinski et al. 2007) the tracking data used in this study had to be collected manually from non-transmitting devices. The data collected demonstrated potential for aerial fire suppression case studies.
FPInnovations early helicopter tracking testing (Ault et al. 2012b)	Presented drop location and volume data to determine the capability and accuracy of available systems at the time.	Demonstrated the utility of the data and tested the precision. The tracking systems tested were slightly (11 %) under reported drop volumes compared to measured volumes, while drop locations were within 21m of measured ground locations.
Country Fire Authority aircraft impact on small fires (McKern and Patterson 2019)	Used aircraft tracking data and fire progression data to determine if aircraft drops were inside, outside or on the final fire perimeter	Demonstrated that drop location data is suitable for application to drop effectiveness evaluation studies
Skimming airtankers in Ontario (Clark and Martell 2020)	Used the tracking data to analyse aircraft use during the initial attack.	Developed methods for estimating drops and fill times from airspeed and altitude data. Showed that tracking data is useful for determining turnaround and service times that could be applied for modelling productivity.
US Forest Service Aerial Firefighting Use and Effectiveness Study (USDA 2020) and Aviation Use summary framework (Stonesifer et al. 2021)	Used data from ATU's mounted in aircraft to log the location of door events coincident with airtanker drop locations in combination with other data on fire events and environmental conditions.	Recommended further use of ATU data for building datasets on aircraft use. They also developed aviation use summaries to help fire managers target aircraft engagements to places where actions are likely to be most effective and where risks align with the values being protected.
BNHCRC investigation of aircraft tracking data for research (Simpson et al. 2022)	Presented initial evaluations of aerial suppression using tracking data and interviews with personnel involved in the suppression using data from the 2019/20 fire season in NSW.	Found that aerial suppression event and tracking data has great potential to enable deep analyses of aircraft use and effectiveness during real bushfire responses when combined with other contextual data. The study also found significant gaps in existing Australian aircraft event records.
Colorado State University study locating airtanker drops in the western United States (Magstadt et al. 2024)	Used airtanker tracking data to determine drop locations without event data. The method could be used to develop datasets of airtanker drop locations and times.	Their methodology can be applied to airtanker tracks to reliably identify drop locations and times.

TABLE 6 PREVIOUS APPLICATIONS OF RESOURCE TRACKING AND EVENT DATA FOR AERIAL SUPPRESSION

Data on suppression objectives, specific application methods and fire and environmental conditions (weather, terrain, vegetation, fuel) is essential for providing the context to aircraft tracking and event data that is required for supporting meaningful analyses. The compilation of such datasets can require significant effort and data records are often found to be missing critical information (e.g. Thompson et al. 2013; Stonesifer et al. 2016; Thompson et al. 2017; Plucinski et al. 2021; Stonesifer et al. 2021; Simpson et al. 2022). This data can come from a range of sources, with some available from agency databases and other records. Some other required data, such as drop objectives and outcomes, are not available within most existing systems, so need to be collected through interviews or surveys of firefighting personnel. Information on broader suppression objectives may be available through incident records, such as situation reports and incident action plans, however these may not always directly link to air operations.

5) Concluding discussion

The use and effectiveness of firefighting aircraft in Australia is largely unknown, despite the significant amount of public money spent on them. Understanding situations where they are beneficial and those where they are not help allow their effective use to be prioritised and therefore improve their overall effectiveness. Restricting the use of aircraft in conditions where they are less likely be effective also helps to alleviate the scarcity of these limited resources (Belval et al. 2020) and reduces the aircrew exposure to accidents (Stonesifer et al. 2014).

Aircraft use studies provide a deeper understanding of how and when aerial firefighting is conducted, which can be compared with intended use and will also provide scale and context to the results of effectiveness studies. There are many aircraft drop variables that could be considered in aircraft use studies (Table 2). Many of these have not been investigated and most current knowledge comes from research undertaken in the US. The findings of these US studies are not directly applicable to Australia, as firefighting aircraft are used differently due to differences in fleet size and composition, tactics, vegetation, weather and terrain.

Many previous studies of aircraft use and effectiveness have been limited by data availability (e.g. Thompson et al. 2013; Calkin et al. 2014b; Stonesifer et al. 2015; Stonesifer et al. 2016; Simpson et al. 2021). Studies that have collected their own observational data have required considerable effort and expenses to do so (e.g. George 1990; Plucinski et al. 2011; Center of Excellence for Advanced Technology Aerial Firefighting 2020; USDA 2020). There are multiple ways of collecting data on aerial suppression effectiveness, each with advantages and disadvantages (Table 7). A combination of different methods is required to provide a complete dataset covering all the different aspects required to support a rigorous analysis.

Methods and sources	**Advantages**	**Limitations**
Field experiments (specifically designed to investigate aerial suppression drops)	Ability to measure many variables precisely. Can be planned to target specific conditions of interest.	Expensive and logistically difficult to organise and conduct. Small number of observations for high cost and effort. Exposed to changing weather that may limit the ability to make comparisons between tests. May not be able to represent challenging fire weather conditions
Field assessments made at bushfires (dedicated observers making measurements from the ground and air)	Can potentially collect high quality observations of drop effects and environmental conditions. Observations representative of wildfire conditions.	Difficult to safely access locations on the ground while being impacted by fire. Aerial observation is expensive to undertake May be limited by low fire activity in accessible areas Presence of observers may influence operations. Post incident ground assessments may not be able to locate or map suppressant drop areas or determine ground actions
Resource tracking and event logging systems	Precise capture of timing and location data of aircraft. Passive data collection that does not influence operations.	Needs to be supplemented with information on drop objectives, fire and environmental conditions to provide a fully analysable data set. Logging systems may not be installed or operational in all aircraft.
Interviews and surveys (of key firefighting personnel)	Can provide information on objectives outcomes. Can potentially provide other contextual information and supporting documentation, including imagery.	Some outcome information may be biased. Accuracy of data will decline with time since events.
Records of fire incidents and environmental conditions (from fire, land management and weather agencies)	Often the only source of supporting information covering suppression actions, fire behaviour and progression, community impacts, fuel and terrain	Incident records may lack detail. Fire progression mapping can be infrequent and sporadic. Weather stations can be distant from fires.

Methods and sources	Advantages	Limitations
	maps and weather observation.	Post fire impact data may not be available for some time. Fuel and vegetation data may be general for a broad area.
Airborne remote sensing	Can provide information during incidents and allow the monitoring of drop effects on fires. Infrared imagery can sense fire activity through smoke.	High cost. Requires regular calibration due to changes in solar influx and cloud cover.
Satellite based remote sensing	Can provide location perspectives before and after fires. Low cost.	Can only detect larger coloured (retardant) drops (though can be supplemented with aircraft tracking data). Limited by times of capture. Often obscured by smoke and clouds.

TABLE 7 ADVANTAGES AND LIMITATIONS OF DIFFERENT DATA COLLECTION METHODS AND SOURCES FOR AERIAL SUPPRESSION EFFECTIVENESS STUDIES

The *Why fly?* project aims to combine data from as many sources as possible to cover aerial suppression operations at bushfires in a wide range of conditions. Aircraft telemetry data, providing tracking and event location and timing, represents a great step forward that has yet to be used to its full potential (Simpson et al. 2022). The National Aerial Firefighting Centre's (NAFC) aerial firefighting aircraft management system (ARENA) contains records of previous aircraft movements and events that will be an important data source for the project. Essential data on aircraft and incident objectives will be sourced through interviews with key personnel, while background information on fire incidents, including fire behaviour and progression, fuels and terrain will come from agency records and weather data from Bureau of Meteorology station observations. Information on ground crew actions, including the timing of follow up suppression is likely to be one of the more difficult data types to obtain and may not be available for all drops studied. It will be important for information on drop objectives to link to broader incident objectives, as this will allow a better assessment of unclear objectives, such as reducing fire intensity and slowing fire spread (Stonesifer et al. 2021).

The *Why fly?* project will also develop methods for automatically detecting drop objectives from available data, particularly using the timing and locations of drops with respect to mapped features, such as buildings and infrastructure and the fire edge. These methods will allow the project to investigate more drops from events data but will need to be verified against drops studied during case studies where objectives have been determined from interviews.

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