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Fighting fire in the heat of the day: an analysis of operational and environmental conditions of use for large airtankers in United States fire suppression

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Abstract. Large airtanker use is widespread in wildfire suppression in the United States. The current approach to nationally dispatching the fleet of federal contract airtankers relies on filling requests for airtankers to achieve suppression objectives identified by fire managers at the incident level. In general, demand is met if resources are available, and the dispatch model assumes that this use is both necessary and effective. However, proof of effectiveness under specific conditions of use in complex environments has not been empirically established. We geospatially intersected historical drop data from the federal contract large airtanker fleet with operational and environmental factors to provide a *post hoc* assessment of conditions of use for the 2010–12 fire seasons in the conterminous United States. Our findings confirm previous results demonstrating extensive use in extended attack. Additionally, we show that use is generally within guidelines for operational application (aircraft speed and height above ground level) and often outside of environmental guidelines suggestive of conditions conducive for most effective use, including drop timing with respect to response phase (initial attack *v.* extended attack), terrain, fuels and time of day. Finally, our results suggest that proximity to human populations plays a role in whether airtankers are dispatched, suggesting that prioritisation of community protection is an important consideration. This work advances efforts to understand the economic effectiveness of aviation use in federal fire suppression.

Additional keywords: aerial suppression, fire economics.

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Introduction

Wildfire suppression organisations around the world utilise aircraft to deliver retardant to manage wildfires. Fleet composition, including a mixture of fixed and rotor wing aircraft, and the retardant capacities and tank system employed, all vary by country. Federal agencies with wildfire suppression responsibility in the United States (US) have historically maintained a mixed fleet of aviation resources composed of helicopters, scoopers, single engine airtankers and a national fleet of US Department of Agriculture, Forest Service (USFS) contract large airtankers (LATs). In the US, LATs have been historically defined as fixed-wing aircraft equipped with 1800 gal. (6814 L) capacity tanks. A modernised fleet with an emphasis on turbine power and increased tank capacity has shifted this definition to aircraft with minimum capacities of 3000 gal. (11 356 L). The 'very large airtanker' (VLAT) classification is a subset of the heavy airtanker category and refers to planes with at least 8000 gal. (30 283 L) tanks; currently the DC-10 is the only VLAT model represented in the federal contract fleet. These LATs are one of the most iconic symbols of wildfire suppression and are a critical part of the aerial firefighting programme. LATs also account for a significant proportion of federal fire suppression aviation expenditures (17.6% average from 2007 to 2011; Calkin *et al.* 2014) and federal wildland firefighter fatalities (17.0% from 2000 to 2012; Stonesifer *et al.* 2014).

The current approach to dispatching LATs across the US relies on filling demand for LATs to achieve suppression objectives identified by fire managers and agency administrators, primarily at the incident level. Because these LATs are national resources, there is a level of centralised national management involved in prepositioning and allocation decisions, particularly during periods of widespread fire activity and associated resource scarcity. Despite this, aircraft demand is ultimately generated at the incident scale. Requests for LATs are placed through a national all-hazards dispatch system, and incident managers and operations personnel can initiate these requests across multiple levels. Generally, this decision-making hierarchy follows the chain of command established by the Incident Command System. For new ignitions or emerging incidents, there may be a single responder at the earliest stages, and they are responsible for placing orders for any initial attack resources that cannot be met locally. Once an LAT responds to an emerging incident, operations personnel on the ground usually direct tactics related to drop targets and objectives. When LATs are used on more complex incidents, this frequently involves additional specialised personnel associated with an aerial supervision module. Typically, a tactical pilot and a trained observer circle above the fire in a small fixed-wing aircraft to observe and coordinate airspace manoeuvres, identify needs for aviation actions and communicate individual tactical actions relayed by ground personnel (National Wildfire Coordinating Group (NWCG) 2014). This aircraft sometimes fills a dual role as a lead plane guiding airtanker drops.

A central assumption in this system of ordering, using and holding resources is that the specific resources are used when they are needed to meet incident management goals, and that this use is both necessary and effective. This applies equally to LATs. Anecdotal evidence suggests that LATs are highly effective under certain conditions; however, proof of effectiveness at meeting stated objectives under the range of conditions of use has not been widely established through field-based measurements. In this manuscript, we incorporate an additional year of data (2012) to expand on previous efforts by Thompson *et al.* (2013) and Calkin *et al.* (2014) to characterise LAT use by suppression phase (initial attack (IA) *v.* extended attack (EA)) and containment outcomes (contained *v.* escaped). Further, we provide an objective characterisation of 2010–12 operational (flight) and environmental (time and space) conditions of national-scale LAT use in the US. These efforts broaden the knowledge base of LAT use and effectiveness patterns, which makes incremental progress towards conducting an economic efficiency analysis of aviation use in federal fire suppression.

Literature review

The effectiveness of retardant on fire has been studied for over 50 years. Wildland fire suppression works to upset the balance of fuel, oxygen and heat in combustion to reduce or extinguish flames and delay or halt the progression of fire. LATs generally accomplish this by dropping water or chemical retardant directly on flames or the fire edge, parallel to or just ahead of the fire perimeter, or in areas removed from the fire front to pre-treat and reduce the flammability of fuels at strategic locations (NWCG 2014). The extensive body of literature related to aerial fire suppression research is well summarised by Giménez *et al.* (2004). Much of this historical work focussed on the physical and chemical properties of the retardant compounds and the effect of the quality of these properties on fire behaviour. This research was mainly laboratory based or involved experimental fires with small sample sizes (e.g. George *et al.* 1977; Blakely 1983, 1985, 1990; Johnson and George 1990). Jewel *et al.* (1974) and George (1982) analysed flight parameters from actual operational missions, but for each study, the sample was limited to a single aircraft model with a limited geospatial scope. Environmental characteristics affecting retardant delivery and effectiveness (landscape slope, fuel type, canopy density, wind speed, and fire behaviour conditions such as flame length and rate of spread) have also been studied under experimental conditions (e.g. Viegas *et al.* 2002; Pastor 2004; Vega *et al.* 2007; Pérez *et al.* 2011). However, experimental drops are expensive, and the resulting limited samples preclude statistical assessment of the range of environmental and operational conditions likely to influence effectiveness in suppression operations.

Research into the operational parameters associated with aerial delivery of retardant has faced similar challenges, but has yielded some general conclusions regarding conditions of effectiveness. Robertson *et al.* (1997) determined that the main factors affecting patterns of aerially delivered retardant were flight speed and altitude, wind velocity, tank geometry and the physical properties of the retardant additives. Recent work by Legendre *et al.* (2014) examined the differences in drop patterns related to drop delivery characteristics and tank systems used. The early phase of the Operational Retardant Effectiveness (ORE) study identified issues with line gaps and highlighted the importance of line continuity. This work verified a critical need for improved consistency in drop patterns, resulting in the implementation of intervalometers in tank control systems (George 1984). Commissioned in the 1980s by the USFS, ORE efforts collected years of operational observations of retardant use. The ORE study aimed to answer the basic question ‘How much chemical or retardant is needed to do a given fire suppression job?’ (George 1992). ORE observations led to significant contributions in aviation safety and operations, notably, the development of *Ten principles of retardant application* (George *et al.* 1989). These guidelines were adopted by the NWCG and accepted by the aviation community as a best practices field reference (see NWCG 2014). Some of the operational principles include ‘Use the proper drop height’, ‘Apply proper coverage levels’ and ‘Monitor retardant effectiveness and adjust its use accordingly’. Despite these contributions, due to operational and environmental complexities previously described, the ORE study was ultimately unable to address the primary research objective (USDA Forest Service 1990).

Australian researchers have also contributed to the body of work related to aviation effectiveness. The Bushfire Cooperative Research Centre published an operational study (Plucinski *et al.* 2007) that extensively explored past research and characterised aerial fire suppression effectiveness in Australia based on field observations. Most recently, Plucinski and Pastor (2013) studied the interaction of retardant and fire for an experimental Australian wildfire through human observation and remotely sensed measurements of changes in fire intensity and rate of spread due to airtanker drops. They devised a methodology for documenting and observing drops and outcomes, which demonstrates an operational model for capturing field-based measurements of LAT drops through coupled ground and aerial platform observations. Both of these efforts contribute to the growing understanding of conditions of effectives, but each suffers from issues related to small samples and the highly complex interaction of operational and environmental factors at play.

The Aerial Firefighting Use and Effectiveness (AFUE) study is a current effort underway in the US aiming to characterise operational use of aviation in fire suppression (USDA Forest Service 2015). The scope of this multi-year project was recently expanded, partially in response to a US Government Accountability Office report (GAO 2013), which found that federal fire agencies had failed to collect basic data on the use and effectiveness of airtankers in fire suppression. AFUE efforts will provide human-assessed and remotely sensed field measurements of retardant and fire interactions from actual field conditions. In addition, field crews will extensively characterise fuels, weather and terrain at the drop location, and drop objectives will be documented, including information on how they relate to the broader suppression objectives beyond the scale of an individual drop. This project will provide a plethora of observation data, and will likely make significant contributions to the body of knowledge regarding aviation use and effectiveness. Still, the ability to collect a sufficient sample of drops across the range of suppression objectives and aviation platforms has yet to be determined, mainly due to the logistical challenges of safely engaging observational field crews at strategic viewpoints in an active suppression incident. Aircraft-based infrared platforms will enhance these ground-based efforts and increase objectivity of the observation data, but this approach also has yet to be deployed extensively in the field. Given the scope of work and the need to document drops across a wide range of objectives, aircraft, and spatiotemporal conditions, a statistically robust sample will take several years to amass.

Best practices guidelines

From the NWCG *Interagency aerial supervision guide* (NWCG 2014), some factors influencing drop effectiveness and coverage levels include pilot skill, aircraft make and model, and associated tank and door systems, drop height, drop speed, drop manoeuvres, wind (speed and direction), flame length, canopy density and availability of ground forces at the drop location. Although few empirical studies have provided operational data on conditions of effective retardant use, given our basic understanding of fire science and combustion, as well as an immense body of operational knowledge from aviation and fire management professionals, there are some generally accepted truths for retardant use and the parameters of effectiveness. Operationally, retardant must be delivered with a regulated flow rate to the ground surface in advance of approaching flames in a continuous swathe of chemicals of sufficient coverage and continuity to affect fire spread and prevent the fire from burning through gaps in the retardant line (Interagency Airtanker Board 2013). Retardant is most effective at suppressing ground fire under conditions with broken or light fuels, and a thick canopy can prevent retardant from penetrating the canopy fuels. Dense fuel models will require retardant delivery at higher coverage levels, and dense canopies may altogether preclude effectiveness regardless of coverage thickness (e.g. NWCG 2014). Airspeed and drop altitude influence LAT effectiveness because increasing aircraft speed lengthens retardant lines and reduces coverage levels through increased drift (e.g. Davis 1959; Solarz and Jordan 2000) and higher drop altitudes result in wider footprints with less coverage, allowing more time for wind to dissipate or shift retardant away from the target locations (e.g. Solarz and Jordan 2000). LATs are generally ineffective in winds in excess of 25 kn (12.9 m s^{-1}; NWCG 2014).

Fuels, slope and time of day all affect fire spread by modifying flame length and fire behaviour. Direct attack with retardant at the prescribed coverage level based on fuel type is generally effective at flame lengths up to 4 ft (1.2 m). Longer flame lengths (4–8 ft; 1.2–2.4 m) require increasingly higher coverage rates. Retardant is generally not effective at flame lengths greater than 8 ft (2.4 m) unless applied in heavy coverage levels and wide line widths (NWCG 2014). Slope steepness influences retardant effectiveness because the physical limitations of aerial delivery may make it difficult to paint thick and continuous retardant lines on steep slopes and increasing slopes contribute to longer flame lengths and increased rates of spread due to the effects of preheating and draft caused by heated air rising upslope (NWCG 1986). Time of day affects fire behaviour through diurnal changes in temperature, relative humidity (RH) and local wind patterns, among other factors. In the western US, the hottest and driest conditions generally occur in the late afternoon. Wind patterns exhibit more variability across days, but winds often become more active and erratic late in the day due to the effects of solar heating and the creation of more local winds.

A multitude of factors is at play to deliver retardant within the bounds of these best practices guidelines. In this work, we will provide a novel and extensive characterisation of the range of operational and environmental characteristics of LAT use in actual wildfire incidents to address basic questions of conditions of this use (timing, location, delivery parameters and environmental conditions at the drop location).

Methods

The gap between the current state of knowledge and the information needed to inform an economically efficient LAT programme is large, and incremental progress is necessary to work towards an end goal of economic efficiency. Characterising LAT use in fire suppression is a prerequisite for any kind of economic efficiency analysis; the current system-wide lack of data on both environmental and operational conditions surrounding LAT drops precludes these efforts. The ongoing AFUE field study will play a key role in this process by providing detailed characterisation of drop conditions, objectives and outcomes for a sample of drops across multiple fire seasons. However, to demonstrate that this sample is statistically significant, the population of drops must first be described.

We expand on previous efforts linking geospatial drop location data to unique wildfire incidents presented by Thompson *et al.* (2013) and Calkin *et al.* (2014), to provide a *post hoc* characterisation of the population of LAT drops from the federal fleet. We first add an additional year of drop data to our analysis; then we widen the scope of previous efforts to describe the spatial and temporal conditions of retardant delivery pertaining to the patterns of flight at the time of the drop (operational) and characterisation of the ground surface affected by fire (environmental). Aircraft sensors designed to monitor airframe stress automatically collect flight data coincident with drop occurrence. Rokhsaz *et al.* (2014) analysed 2008 and 2009 data to characterise usage and manoeuvre load spectra during all phases of the flight sequence. In contrast, we provide a national, multi-year summary of these data with a focus on operational factors influencing effectiveness – specifically airspeed at the time of the drop and altitude above ground level (AGL). Routine data collection efforts by federal agencies do not record drop timing, ground conditions or fire behaviour information beyond the scale of the individual drop, or series of drops. There is a wealth of

Table 1. Summary of data sources

Description of data sources by analysis category are provided, including references. Analysis categories are divided into operational and environmental bins. Operational summaries characterise the conditions of retardant delivery related to the aircraft operation, and environmental summaries characterise the general location of the ground affected by the retardant drop, including some non-environmental characteristics (day of year and hour of day) that can help describe potential fire behaviour and weather in the absence of actual data for these factors. Data source acronyms include Operational Loads Monitoring Systems (OLMS), United States Geological Survey National Elevation Dataset (USGS NED), Wildland Fire Decision Support System (WFDSS), Landscape Fire and Resource Management Planning (LANDFIRE) and National Highway Planning Network (NHPN)

Analysis category	Analysis parameters	Data	Source
Operational	Flight data	Airspeed	OLMS
		Altitude (above mean sea level)	OLMS
		Ground level elevation	USGS NED 1/3 arc second digital elevation model (Gesch *et al.* 2002; Gesch 2007)
Environmental	Timing	Day of year	OLMS
		Hour of day	OLMS
	Location	Geographic Coordinating Area (GCA)	WFDSS (Noonan-Wright *et al.* 2011)
	Fuels	Anderson fuel model	LANDFIRE (Anderson 1982; US Geological Survey 2013)
		Mean canopy height	
	Terrain	Percentage slope	USGS NED 1 arc second digital elevation model (Gesch *et al.* 2002; Gesch 2007)
	Human populations and values	Wildland–urban interface/intermix (WUI)	SILVIS (SILVIS Laboratory 2012)
		Major highway	NHPN v 11.09 (US Department of Transportation 2011)
		Designated wild place (Federal Wilderness, Inventoried Roadless Area, Wild and Scenic River Area)	WFDSS (Noonan-Wright *et al.* 2011)
		Population count	LandScan™ (Bright *et al.* 2012)
		Federal critical habitat for endangered and threatened species	WFDSS (Noonan-Wright *et al.* 2011)

information within the cockpit at time of the drop, but there is no system in place to collect and synthesise this information for investigation of usage patterns at a wide spatial scale. We intersect drop data with geospatial data to provide a quantification of the distribution of drops related to the drop environment, including time of day, day of year, administrative location, fuels, terrain slope and proximity to human populations. Temporal characteristics provide an indirect environmental summary due to diurnal and annual effects on fuel conditions and potential fire behaviour. Table 1 summarises the analysis categories and data sources used, which we describe fully in the following paragraphs.

Our approach utilises door-opening events logged by Operational Loads Monitoring Systems (OLMS) sensors installed onboard federal contract LATs. The OLMS instrumentation is primarily designed to monitor airframe loads and stresses experienced during the operational life of the LAT; however, because it also uses a global positioning system to log geospatial coordinates (latitude and longitude) and pressure sensors to log altitude and airspeed coincident with tank door actuation, we are able to use these data to infer retardant drop locations. We manually linked these geospatial coordinates with fire location data and resource order information to associate drops to unique incidents and to determine whether the drops occurred during IA or EA operations. This classification is based on the Resource Ordering and Status System (ROSS) dispatch data, according to methods described by Calkin *et al.* (2014) that utilise the timestamp from the first ROSS order to establish a response timeline. The first 24-h period and associated suppression actions are classified as IA, and anything occurring after this is EA. The potential limitations and rationale provided for this approach are discussed at length in Calkin *et al.* (2014).

Next, we examined operational parameters for retardant delivery, specifically flight speed and altitude AGL when the OLMS sensor logs a drop event; we then compared these values to operational guidelines. The current USFS contract LAT fleet is composed of over 20 tankers representing at least seven different aircraft makes and models with a range of capacities (e.g. Lockheed P2V, 2000 gal. (7571 L); British Aerospace 146/RJ85, 3000 gal. (11 356 L); McDonnell Douglas DC-10, 11 600 gal. (42 911 L)). However, the federal fleet composition has changed significantly over time. From 2000 to 2012 the fleet consisted of a maximum of eight Lockheed P-3 Orions (2700 gal.; 10 221 L), which were only in service in 2010 and early 2011, and up to 10 P2Vs. Operational guidelines for retardant delivery may vary with the performance capabilities of different aircraft, but due to the relative uniformity in fleet configuration from 2010 to 2012, we can utilise general guidelines for operational parameters. Although pilot discretion ultimately determines safe altitudes for operational retardant delivery, federal contract documents for P2V aircraft specify a lower ceiling of 150 ft (45.7 m) and a target altitude of 200 ft (61.0 m) above the ground or canopy cover. Similarly, the suggested operational range for LAT flight speed at the time of a drop is described in the *Interagency aerial supervision guide* as 120–140 kn (61.7–72.0 m s^{-1}; NWCG 2014). Flight speed corresponding with a door-opening event is logged on the sensor, and these data required no pre-processing for analysis. In contrast, altitude data are provided in feet above mean sea level (measured from barometric pressure). To analyse the distribution of drop heights AGL we intersected drop locations with a 1/3 arc second (~10 m) digital elevation model (DEM; Gesch *et al.* 2002; Gesch 2007) and subtracted the ground surface elevation from the reported aircraft altitude. A subsample of drops occurred in locations with coincident light detection and ranging (LiDAR) footprints. LiDAR provides a finer spatial resolution DEM at 1/9 arc second (~1 m; Gesch *et al.* 2002; Gesch 2007). For those drops, we repeated our methods to verify that our approach was similarly approximating altitude AGL when using elevation datasets of different spatial resolutions. We then incorporated 30-m LANDFIRE mean canopy height data (US Geological Survey 2013) to arrive at drop height above the canopy, if present. Finally, we compared the mean or median (depending on whether the data were normally distributed) plus a measure of dispersion (standard deviation (s) or interquartile range (IQR)) to specified operational ranges.

To characterise the environmental conditions at the drop location, we first analysed the temporal patterns of use. To facilitate analysis of seasonal patterns of use, drop dates were converted to numerical day of year. To address diurnal variability in weather conditions and the effects of this on fuel moisture and associated fire behaviour we also examined drop time of day. We converted drop timestamps from Coordinated Universal Time (UTC) into local time, then categorised by drop hour. To capture daily fluctuations in fire activity following diurnal weather changes, we binned drop hour into the following categories for analysis: morning (0700–1159 hours), early afternoon (1200–1459 hours), late afternoon (1500–1859 hours) and evening (1900–2159 hours).

Next, we used a geographic information system (GIS) to spatially intersect incident-linked drop location data (door-opening events) with geospatial landscape data of interest (environmental factors). We first extracted information on the general location based on Geographic Coordinating Areas (GCAs). GCAs are national-scale, multi-agency planning units designated by wildland fire protecting agencies to provide effective allocation and prepositioning of emergency management resources (National Multi-Agency Coordinating Group 2015). We then extracted 30-m LANDFIRE vegetation data (versions LF_1.1.0 and LF_1.2.0; US Geological Survey 2013), specifically, Anderson fire behaviour fuel models (Anderson 1982) and mean canopy height. The 13 Anderson fuel models and non-burnable LANDFIRE data categories were classified by majority fuel type: grass, shrub, timber, slash and non-burnable. Classification of terrain steepness is subjective and depends on the geological characteristics of the slope in question and the intended activity affected by the steepness categories; there is no official designation for slope steepness related to airtanker drops. Because it is widely used and national in scale, we followed guidelines from the Natural Resource Conservation Service's *Soil survey manual* (Soil Survey Division Staff 1993). Percentage slope was extracted from a 30-m DEM (Gesch *et al.* 2002; Gesch 2007), then categorised as flat (<5%), moderately sloped (5–15%), steeply sloped (15–25%) or extremely sloped (>25%). We used the 30-m DEM for this application rather than the 1/3 arc second (~10 m) DEM to more appropriately characterise the general slope in the vicinity of the drop for highly variable terrain. Our final spatial analysis assessed the proximity of LAT use to human populations, including whether drops occurred within SILVIS wildland–urban interface/intermix (WUI; SILVIS Laboratory 2012) and designated wild places (Federal Wilderness, Inventoried Roadless Area or Wild and Scenic River Area). Linear distances from the drop location to the nearest WUI boundary, wild place and major highway were calculated in a GIS (see Table 1 for data source details). Finally, we used LandScan$^{\text{TM}}$ population data (Bright *et al.* 2012) to sum total human population within a 10-km buffer of the drop. We also intersected drops with federal critical habitat boundaries. Our analysis did not distinguish whether fire occurrence associated with suppression actions would have a net positive or negative effect on critical habitat; we simply investigated the spatial relationship of critical habitat and LAT use to explore potential explanations for LAT use in wilderness.

We accept some limitations with our approach stemming from limitations in the underlying data. First, the OLMS dataset does not include every drop from every LAT involved in federal fire suppression. The USFS contract LATs are the only suppression aircraft with OLMS drop location data for 2010–2012. Further, the OLMS sensors installed on the next-generation jet-powered tankers bought on contract in 2011 and 2012 were not properly functioning; thus, they provided no drop records. Military C-130s equipped with Modular Airborne Firefighting Systems (MAFFS), state-owned aircraft (notably California Department of Forestry and Fire Protection planes) and Canadian LATs, all of which play significant roles in US wildfire suppression in certain fire years, also do not contribute drop location data to this sample. Finally, there are some temporal lapses in data for reporting LATs due to sensor malfunction or data delivery issues. Still, as identified in Calkin *et al.* (2014), the sample is spatially and temporally diverse and represents the majority of LAT use in fire suppression for the three years of interest. We chose not to include 2013 fire season drop data in our analysis because, due to the historically small contract LAT fleet size and the associated heavy reliance on surge capacity tankers during an abnormally active fire year, the true use of LATs for that year would not be represented by drop data coming only from the contract LAT fleet.

OLMS data also do not provide any information on the type of material delivered from the plane or the tactics at play. Chemical retardant is widely used in the US, and individual airtanker bases track total gallons delivered each fire season. This information cannot be consistently linked back to individual drops or even unique incidents due to a lack of detail in data collection practices for federal incidents and resources. Some of the LAT drops in our sample may involve water delivery; however, due to the predominance of retardant use in US LAT suppression practices and for the purposes of semantics in this manuscript, we will assume that all drops discussed here involved delivery of long-term chemical fire retardant. Although some OLMS units log delivery parameters like flow rates and volume delivered, these data were not reliably available in our dataset; therefore, in the absence of data on split loads, we assume all drops are full loads.

Our approach also accepts that geospatial data must generalise a heterogeneous environment to some degree. We assume that the drop location identified by a door-opening event is a static point in three-dimensional space. In fact, it is associated with a drop trajectory affected by a multitude of factors including flight speed and heading (direction), selected retardant coverage level, aircraft altitude AGL, chemical composition, delivery system and winds at the precise drop location. Data essential to the characterisation of individual drop trajectories, particularly wind speed, direction and chemical composition, are not available at the single drop scale. Therefore, we do not attempt to project the retardant trajectory onto the ground surface.

Results

Drop data summary statistics are presented in Table 2, including the total number of valid drop data points by year and the number of unique incidents linked to the drops. Because data availability is affected by the number of LATs outfitted with OLMS sensors in the federal fleet, Table 2 also presents the annual contract fleet size range. Total drops were somewhat comparable for the three years of record, despite the fleet shrinking by half, by year 2012. The median value for drops per incident was 4.0 for all sample years. Year 2011 had the greatest representation of drops, including the highest value for drops per incident and measures of variability. These results are explained by historic high fire activity in the state of Texas and associated differences in business practices there, which preclude linking LAT resource orders to specific incidents (see Calkin *et al.* 2014).

Fig. 1 shows the geographic locations of drops by GCA. Point data are interpolated with a kernel density function in ArcGIS 10.2.2. to illustrate the density of drops across the country. Each map depicts total interpolated drops per 4-km grid cell using the default search radius and density results are shown on a colour gradient with the same scale for all four maps. The display showing the collective dataset for 2010–2012 (Fig. 1) demonstrates widespread and geographically distributed use of LATs throughout the West, and the spatial patterns mimic what we might expect from density maps for fire activity for the fire seasons represented (NICC 2011, 2012, 2013).

Response and containment category

Table 3 summarises response and containment from drop data, omitting all records from Texas. The upper portion of the table presents the percentage of total drops in each category. From this, across all years, 50.1% of drops were used in IA and 45.0% were used in EA (4.8% were unclassified). Notably, 75.0% of IA drops occurred on incidents that ultimately escaped IA containment efforts. Our results exhibit some annual variability in the proportion of IA and EA usage, which is expected given the inherent variability in fire season characteristics, but are largely consistent with findings of previous research demonstrating significant use of LATs in EA (Thompson *et al.* 2013; Calkin *et al.* 2014). The lower portion of the table summarises the number of incidents with drops during IA only, both IA and EA, or EA only. There are many more individual incidents with drops just during IA across all three years; however, from Table 2 and previous work by Calkin *et al.* (2014) we see that there are a small number of incidents with a large number of drops (frequently occurring during EA), which ultimately account for the bulk of LAT use nationwide.

Table 2. Operational Load Monitoring Systems (OLMS) drop summary statistics

General summary statistics are provided for federal contract large airtanker drops from 2010 to 2012 OLMS data for the conterminous United States. All drops are assumed to be full loads

Statistics	Year			
	2010	2011	2012	All years
Federal contract LATs[A]	18	11	9	n/a
Total drops	2378[B]	3285[B]	2281	7944
Unique incidents	286	325	272	883
Unknown drops	50 (2.1%)	123 (3.7%)	51 (2.2%)	223 (2.8%)
Drops by incident statistics (omitting unknown drops)				
Mean	8.1	9.7	8.2	8.7
Median	4.0	4.0	4.0	4.0
Standard deviation	13.0	17.5	12.2	14.6
Skewness	4.4	4.6	4.1	4.7

[A] LAT fleet size shown is the minimum for the calendar year.
[B] There are fewer total drops in 2010 and 2011 than shown in Calkin *et al.* (2014) because drops inferred for these years from Automated Flight Following records and resource orders are not included here.

Operational analysis

Fig. 2 presents the frequency distribution of operational drop delivery speeds and altitude AGL for all data. From Fig. 2*a*, ~7% of drops recorded unrealistically slow flight speeds (e.g. less than 51.4 $m\ s^{-1}$ (100 kn)). OLMS sensors do record false positives, particularly when doors jostle during high turbulence, takeoff and landing; however, the data were thoroughly cleaned to remove drops that were not clearly associated with incident records (see Calkin *et al.* 2014). Further, because these data are from a single aircraft, it is likely these errors result from sensor malfunction. The rest of the airspeed data (omitting these errors) indicate a normally distributed sample with a mean of $73.0 \pm 7.0\ m\ s^{-1}$ (142.0 ± 13.6 kn). Nearly three-quarters of the drops (72.2%) fall within 5.1 $m\ s^{-1}$ (10.0 kn) of the general operating range. Fig. 2*b* shows the range of drop altitude AGL (bare ground). Results incorporating LANDFIRE mean canopy height did not significantly alter the distribution of drop height above bare ground or canopy surface; therefore, we present graphical summaries only for the height above bare ground. From Fig. 2*b*, data are skewed to the right (skewness = 9.4) and there are multiple outliers ($n = 158$) in excess of 304.8 m (1000 ft) that are not shown. Median drop height is 66.2 m (IQR = 47.0–95.1 m) (217.3 ft (IQR = 154.1–311.9 ft)). A total of 1906 drops (23.8%) were below the 45.7 m (150 ft) safety threshold. This approach produced a single drop with negative altitude, compared with 59 drops with negative altitudes when we incorporated average canopy height from LANDFIRE data into the methods.

Environmental analysis

Table 4 presents drop data summarised by GCA for several factors of interest (see Table 1), plus a value for measure of dispersion for the entire sample (*s* or IQR), where appropriate. Drop distribution by GCA illustrates that the majority of drop

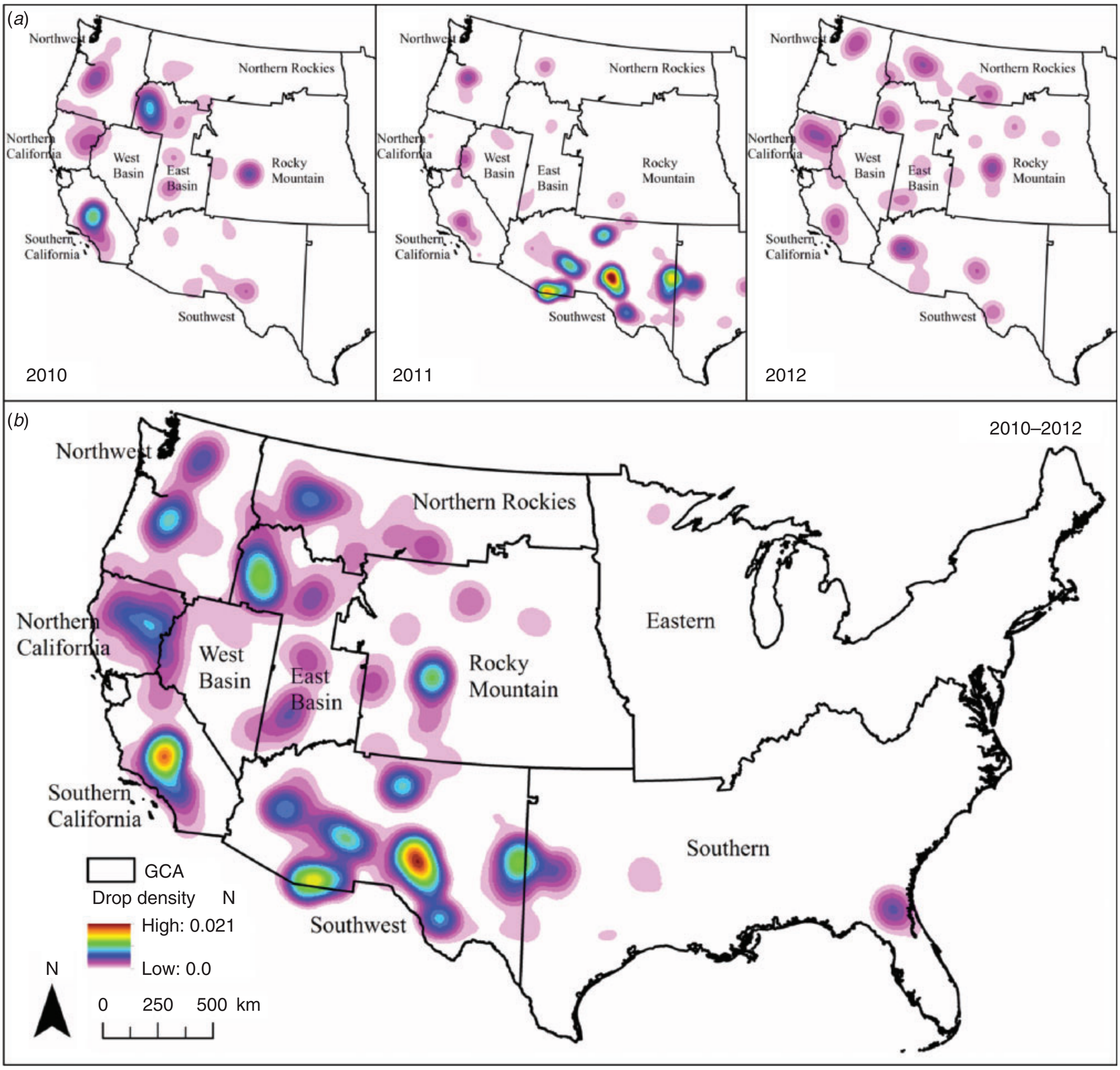

Fig. 1. Drop density maps. GCA, Geographic Coordinating Area.

records occurred in the Southwest GCA (SWA; $n = 2813$, 35.4%). Drop occurrence by region aligns with general patterns of typical fire season occurrence in the US. The earliest mean drop day of year occurs in the Eastern GCA (EAA), which tends to see increased fire occurrence in late winter (January–February) and early spring (March–April) due to an accumulation of leaf litter dried by open deciduous canopies. This is followed by both the SWA, where the fire regime is largely driven by monsoonal moisture and lightning in late spring and early summer (April–June; Keeley *et al.* 2009), and the Southern (SAA) area, which tends to see fires earlier in the spring (March–April) or late fall (October–November). This is coincident with periods with lower RH combined with winds and cured surface fuels to increase fire occurrence (Sommers *et al.* 2009; Lafon 2010). Drops within Federal Wilderness accounted for 7.9% ($n = 627$) of all data. Of these wilderness drops, the SWA had a disproportionately high representation each year for the three sample years (47.5, 85.4 and 56.0% of the total yearly wilderness drops for 2010, 2011 and 2012). Only 313 (3.9%) drops were within SILVIS WUI boundaries. WUI drops occurred most frequently in the SWA with 95 drops (3.4%), although were proportionally highest in the Rocky Mountain GCA (RMA) where 10.3% of drops occurred within the WUI. Finally, 1313 (16.5%) drops intersected critical habitat, most of which occurred within the SWA ($n = 919$, 11.6%).

A histogram of drop occurrence by local hour and majority fuel model is shown in Fig. 3. Only two drops intersected slash

Table 3. Response and containment summaries

Operational Load Monitoring Systems (OLMS) drop records from federal contract large airtankers for 2010–2012 for the conterminous United States (without Texas) are summarised by response and containment category. Texas state drops are omitted due to business practices that prevent the use of resource order records to establish a suppression response timeline. The upper portion of the table depicts percentage total drops by response category, containment category and year. The lower portion provides the annual unique incident count by the response category during which drops occurred. IA, initial attack; EA, extended attack

Response category	Containment category	Year			
		2010	2011	2012	2010–2012
Percentage total drops					
IA	Contained	18.6	6.5	9.8	11.6
	Escaped	42.4	36.7	33.4	37.6
	Unknown	1.8	<0.1	0.8	0.9
	Total IA	62.9	43.3	44.1	50.1
EA	N/A	35.2	50.9	49.1	45.0
Unknown	Unknown	1.9	5.9	6.8	4.8
Count total incidents					
With drops during IA only		231	145	162	538
With drops during IA and EA		38	41	58	137
With drops during EA only		15	34	37	86

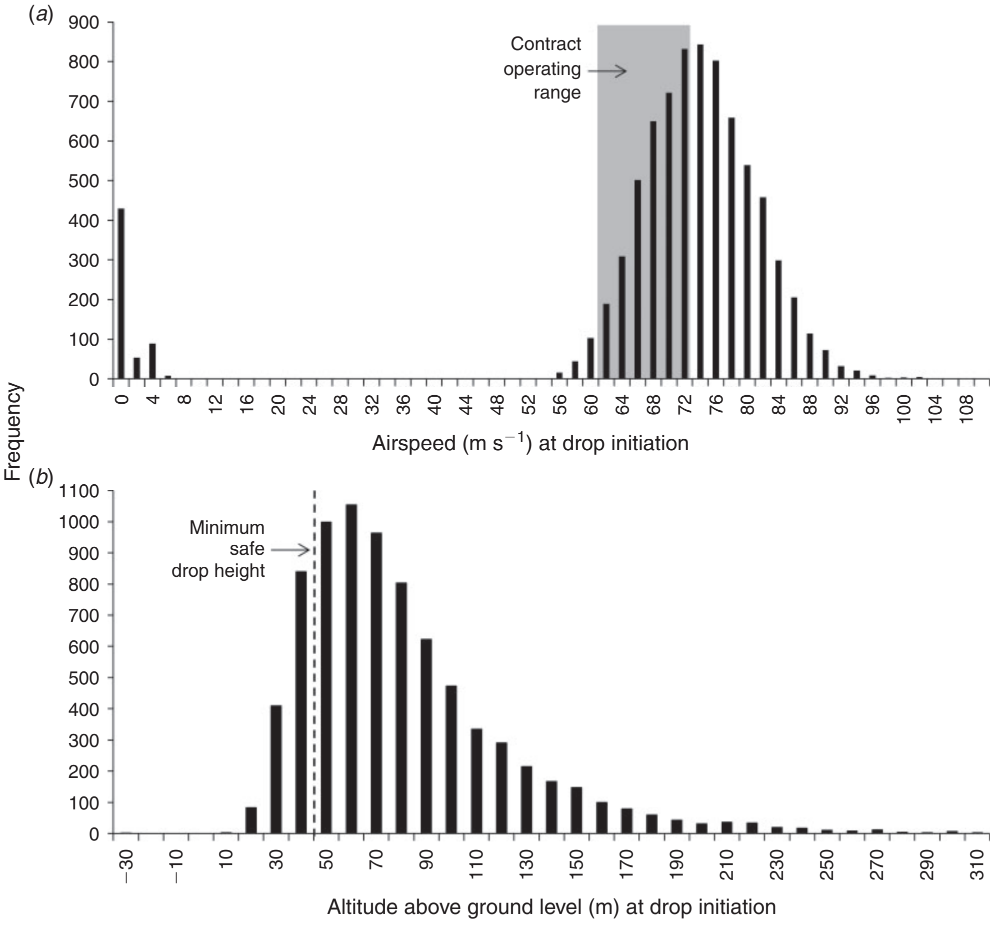

Fig. 2. Distribution of operational metrics.

Table 4. Summary of environmental (general spatial and temporal) use characteristics

Environmental drop characteristics are summarised by Geographic Coordinating Area (GCA) for federal contract large airtanker Operational Load Monitoring Systems (OLMS) data (2010–2012) for the conterminous United States. WUI, wildland–urban interface; s.d., standard deviation

GCA	Total drops (count)	Mean day of year (1–365)	Mean time of day (24-h clock)	Median[A] slope (%)	Wilderness drops (count)	WUI drops (count)	Critical habitat drops (count)
Eastern	53	106	1539	0.0	0	0	7
Eastern Great Basin	1055	218	1608	21.2	52	52	32
Northern Rockies	634	207	1606	23.1	15	7	137
Northwest	663	219	1554	19.4	81	10	64
Northern California	509	211	1531	26.8	13	4	48
Southern California	787	226	1459	37.4	37	39	61
Rocky Mountain	658	201	1524	24.9	13	68	19
Southern	488	179	1609	1.7	3	25	7
Southwest	2813	161	1524	19.4	403	95	919
Western Great Basin	284	220	1618	23.1	10	13	19
All GCAs	7944	193	1539	21.2	627	313	1313
s.d. (total)	–	48	0254	8.7–38.4[A]	–	–	–

[A] Median and interquartile range are presented here because the distribution of slope data is skewed to the right.

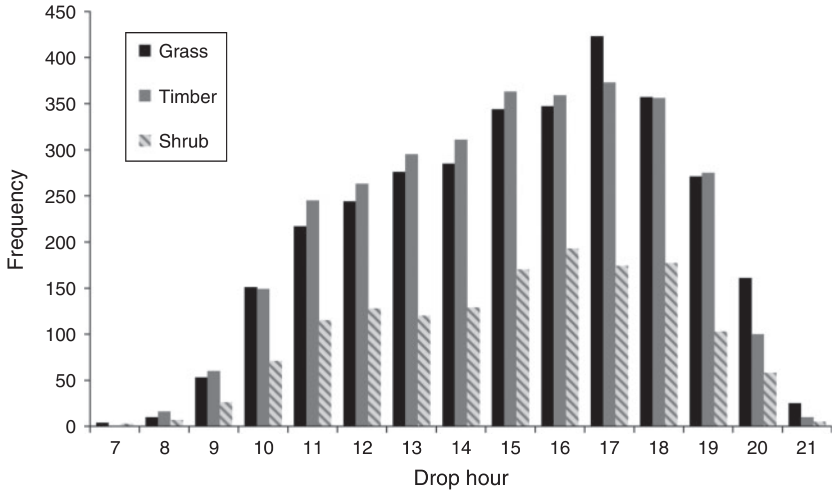

Fig. 3. Distribution of drops by fuel model and time of day.

fuel models; these values and non-burnable data points (2.4% of drops) are not represented here. Most drops occurred in the late afternoon and early evening. This was true for all majority fuel types (Fig. 3), as well as all GCAs (Table 4). Grass (39.5%) and timber fuel models (39.6%) were equally represented, followed by shrub fuel models (18.4%). To emphasise these patterns related to slope steepness, Table 5 summarises drops by time of day, majority fuel type and slope steepness categories. From Table 5, the steepest slope category (>25%) is the most frequently represented across all fuel type and time of day categories (42.9% of data). Drops occur most frequently in late afternoon, for both grass and timber, in extreme slopes.

Our final spatial analysis investigated the proximity of LAT use to human populations. Fig. 4 depicts the distributions of drop distances to WUI, wild places and major highways, as well as total human population within 10 km. From the SILVIS WUI data, only 313 (3.9%) drops were within WUI designated boundaries (Table 4). Although few drops occurred within WUI, many occurred close to WUI (Fig. 4*a*). Median distance to WUI is 4.5 km (IQR = 1.7–9.0 km), and 27.9% of all drops were within 2 km (79.0% were within 10 km). Distance to a major highway demonstrates a similar distribution (Fig. 4*b*); most drops were close to highways (median = 5.4 km, IQR = 2.6–10.3 km). Although there are many drops within Federal Wilderness, Inventoried Roadless, and Wild and Scenic River Area boundaries ($n = 1685$, 21.0%), there are nearly as many drops ($n = 1235$, 15.4%) that were greater than 50 km away from these areas (Fig. 4*c*). Finally, drops generally occurred in proximity to sparsely populated areas based on LandScan™ population data (Fig. 4*d*). Median population within 10 km was 136 people (IQR = 18–1405). A small proportion of the drops had no population within 10 km (5.6%) and the same percentage of drops had communities of 25 000 people or more in the 10-km buffer.

Table 5. Time of day, majority fuel type and slope steepness matrix

The distribution of drops by time of day, general fuel type (grass, shrub and timber) and percentage slope category is shown. Drops are from federal contract large airtanker Operational Load Monitoring Systems (OLMS) data (2010–2012) from the conterminous United States (US). Values shown are proportions of total drops by category. General fuel type is derived from LANDFIRE Anderson fuel model grids (Anderson 1982; US Geological Survey 2013) and slope steepness is from the US Geological Survey's National Elevation Dataset 1 arc second digital elevation model (Gesch *et al.* 2002; Gesch 2007)

Time of day category	Majority fuel type			Proportion by slope category (%)	Slope steepness category (%)
	Grass	Shrub	Timber		
Before 1200	1.2	0.4	0.9	16.4	<5
1200–1500	1.4	0.8	1.9		
1500–1800	2.4	1.1	2.0		
After 1800	1.8	0.8	1.7		
Before 1200	1.2	0.7	1.2	22.1	5–15
1200–1500	2.4	1.0	2.2		
1500–1800	3.5	1.6	2.9		
After 1800	2.4	1.0	1.9		
Before 1200	1.2	0.4	1.1	18.6	15–25
1200–1500	2.1	0.9	2.0		
1500–1800	2.5	1.2	2.5		
After 1800	2.1	0.9	1.7		
Before 1200	2.8	1.2	2.0	42.9	>25
1200–1500	4.8	2.0	4.6		
1500–1800	6.3	2.9	5.9		
After 1800	4.4	2.1	3.8		

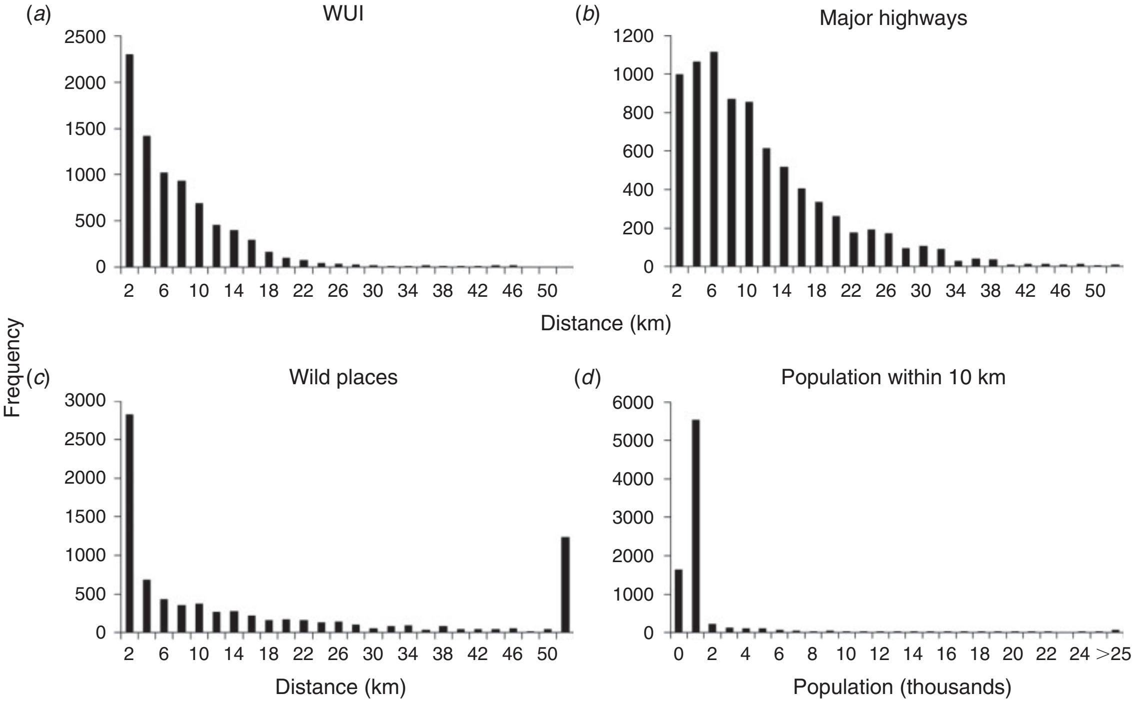

Fig. 4. Proximity of drops to human populations. WUI, wildland–urban interface/intermix.

Discussion

In general, this analysis illustrates that despite guidance stating that the primary mission for LATs is IA (National Multi-Agency Coordinating Group 2015) these aircraft are used in EA nearly half the time (45.0%). For those IA drops, the majority occur on fires that ultimately escape containment efforts (75.0%). Given that the federal wildfire escape rate hovers around 2–3% (Tidwell 2012; US Department of Interior Wildland Fire Management 2012), these results suggest that LATs are used on fires that are inherently difficult to contain and may also indicate objectives at play beyond basic incident containment (e.g. point protection). This is consistent with work by Plucinski *et al.* (2012), who showed that suppression personnel held the perception that aircraft minimised time to fire containment under more challenging conditions. Future work will expand on this topic by analysing IA suppression resources assigned to all federal ignitions, including airtankers, and comparing modelled near-term fire behaviour runs in the absence of suppression actions with actual containment outcomes, specifically investigating those incidents that received LAT drops.

We also show that LAT use in fire suppression tends to fall within operational guidelines. Mean airspeed is generally within the target range, and mean drop altitude AGL is near the target altitude and generally above the safety ceiling (Fig. 2). We expect that because LATs are frequently sent to incidents with inaccessible and variable terrain there are some instances where the DEM did not fully capture the variability of the ground surface, leading to potential error in our approach. Further, the tank door may have been opened adjacent to a cliff or other abrupt change in elevation and our point extraction method falsely characterised the altitude for the majority of the drop trajectory. Diving manoeuvres during retardant delivery would have a similar effect on our approach, leading to some overestimates of drop height. Finally, the distribution is affected by 158 outliers with altitudes AGL in excess of 304.8 m (1000 ft), which may be instances of jettison or sensor malfunction; we have no way of attributing a cause and these values are not included in the histogram in Fig. 2 or in the summary statistics. In spite of these limitations, we feel this is a sound approach to approximate height AGL *post hoc* and provides a novel summary of actual operational LAT use based on best available data.

In contrast to operational conditions, LAT use for 2010–2012 possibly falls outside environmental conditions that are generally considered precursors to effective use. Retardant application guidelines emphasise that retardant is less effective in situations with flame lengths greater than 8 ft (2.4 m; NWCG 2014). Although we do not have the ability to estimate flame length from these data, our results show that LAT use occurs most frequently under conditions conducive to active fire behaviour and longer flame lengths (steep slopes, hottest part of the day, fuel models with a canopy present; Fig. 3 and Table 5).

The investigation into proximity to human populations revealed some interesting points. From Fig. 4, it is clear that LATs are often used near human populations. Median distance to WUI is 4.5 km and to highways, 5.4 km. This suggests that proximity to human populations plays a role in whether airtankers are dispatched, indicating that prioritisation of community protection is an important consideration. Further, it is likely that sociopolitical demands for LAT use near urban areas affects deployment decisions in some situations. Conversely, many drops do not appear to be associated with WUI. Approximately 20% are more than 10 km away from WUI boundaries, which in certain cases may reflect the ability of LATs to quickly access remote areas. Some of these drops also occur within Federal Wilderness area boundaries. Investigation into the disproportionate representation of wilderness drops in the SWA reveals that this is the third highest GCA for total wilderness area, but when normalised to total land area, it has almost the lowest wilderness density of all western GCAs. It appears that the wilderness use in this GCA is dominated by a small number of large fires; 401 drops were linked to just 16 incidents (two drops were associated with unknown fires). Interestingly, the majority of these SWA wilderness drops (78.4%) were coincident with federally designated critical habitat for the threatened Mexican spotted owl (*Strix occidentalis lucida*), which has ~25 000 km^2 of designated critical habitat in the SWA (2.8% total GCA area). Although episodic wildfire greatly enhances habitat for some wildlife species, wildfire has been identified as a significant threat to Mexican spotted owl habitat due to the potential for catastrophic habitat loss resulting from fire in old-growth forest stands (US Fish and Wildlife Service 1995, 2013). Given this, critical habitat protection may have played a role in decisions regarding suppression of south-western US wilderness wildfires using LATs. On a related note, in 2015 the Department of Interior issued a new wildland fire management strategy that prioritises protection of dwindling sagebrush–steppe habitat from wildfires, to conserve habitat for the previously endangered greater sage-grouse (*Centrocercus urophasianus*) and prevent ecosystem conversion to highly flammable and invasive cheatgrass (*Bromus tecorum*; Jewell 2015). Potential future research may compare patterns of aircraft use, fire size and containment outcomes before and after this significant change in policy to assess the effects of these changes on aviation use related to protection of critical habitat.

Our results confirm earlier research results related to LAT use and challenge a long-held assumption that LATs are applied primarily to assist in the building of line to contain fires during IA. Recent research has demonstrated that large fire management does not follow traditional models of IA, where a fire is contained if the potential capacity of resources to construct fire line exceeds the rate of fire perimeter growth (Katuwal *et al.* 2016). Our results are largely consistent with these findings. There is no doubt a broader range of objectives and missions associated with LATs outside of simply building and linking line (e.g. protecting ground crews, providing point resource protection, etc.); unfortunately, federal agencies have not historically collected data necessary to describe use, objectives or outcomes under these circumstances.

Our results further identify a need for improved monitoring and quantification of how and under what conditions LATs are effective at meeting drop objectives. The frequent use of LATs at the peak of the daily burning period and in steep terrain suggests that LATs may be viewed as a resource of last resort, responding to suppression needs when other resources are known to be less effective or fire conditions preclude safe engagement of ground forces. At present, we have only a partial picture of how fire managers balance potential damages, probability of success and external pressures when calling for LATs or determining drop objectives, and a limited informational basis to help support those decisions. Further, an important factor to consider in moving towards efficiency is the proximity of LATs to fire occurrence. Minimising cycle times between the drop occurrence and reload base can reduce flight time and expenses, enhancing efficiency. Currently, the factors affecting prepositioning decisions for the national airtanker fleet are poorly understood. Further work is needed to understand the current approach to prepositioning and to demonstrate how efficiency could be enhanced through targeted use of fire occurrence forecasting tools to effectively preposition LATs for timely IA response on new ignitions.

Perhaps most importantly, we highlight system-wide deficiencies in data collection related to objectives, conditions of use and outcomes for LAT use. Our *post hoc* analysis provides valuable insight into usage patterns that potentially conflict with generally accepted conditions of effectiveness; however, the lack of detailed information on ground, weather and fire conditions at the precise time and place of an LAT drop precludes definitive conclusions regarding effectiveness. AFUE ground crew data collection efforts will provide field-based measurements of key environmental parameters coincident with LAT drops, which will facilitate future analyses and minimise the need to infer fire behaviour from time of day, fuels and slope at the drop location.

Conclusion

Our current inability to capture drop objectives and link specific actions to subsequent outcomes precludes our ability to draw any conclusion about the effectiveness of the federal LAT programme. Drops that occur outside operational and environmental guidelines may indeed be effective in achieving the specified objectives. Additionally, although the likelihood of success under actively growing fire periods may be low, instances where the potential payoffs in terms of avoided future damage and suppression effort may make such low-likelihood, high-payoff tactics economically justified.

Economic efficiency requires that the expected benefits from each retardant drop exceed the expected cost at the time the decision to order an LAT is made. Estimating expected benefits is highly complex and requires both an understanding of the likelihood that the drop will achieve the identified objective and how that objective contributes to reduced future wildfire damage. Both factors are currently poorly understood. However, the considerable use under potentially challenging conditions at the drop location with respect to environmental factors warrants additional examination and review to determine if the expected relatively low likelihood of success is balanced by very high potential payoffs. The AFUE study is designed to help answer some of these critical questions. If results suggest low effectiveness under the most challenging conditions, efforts to restrict usage under those conditions may be warranted. AFUE data will also facilitate important assessments of risk transference associated with reliance on aviation resources in situations where it would be unsafe or challenging for ground personnel to engage in suppression actions.

Ongoing data collection, monitoring, and evaluation should set the stage for future cost–benefit analyses of LATs, as well as other aerial suppression resources. Essential components of future research include assessing the effect of forecasts on resource prepositioning and allocation decisions, understanding tradeoffs across IA–EA prioritisation, examining marginal cost differences across the use of additional LATs and the more efficient use of existing LATs, if possible, and characterising how and why fire managers make decisions to utilise LATs.

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