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Large airtanker use and outcomes in suppressing wildland fires in the United States

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Abstract. Wildfire activity in the United States incurs substantial costs and losses, and presents challenges to federal, state, tribal and local agencies that have responsibility for wildfire management. Beyond the potential socioeconomic and ecological losses, and the monetary costs to taxpayers due to suppression, wildfire management is a dangerous occupation. Aviation resources, in particular large airtankers, currently play a critical role in wildfire management, and account for a relatively large share of both suppression expenditure and firefighting fatalities. A recent airtanker modernisation strategy released by the US Department of Agriculture Forest Service and the US Department of Interior highlighted cost effectiveness as the fundamental tenet of both the replacement strategy and the use of aerial firefighting resources. However, determining the cost effectiveness of alternative airtanker fleets is challenging due to limited data and substantial uncertainty regarding aerial firefighting effectiveness. In this paper, we significantly expand on current airtanker usage and effectiveness knowledge, by incorporating spatially explicit drop location data linked to firefighting resource orders to better identify the period in the fire history when drops occurred, and through characterisation of the resulting outcomes of fires that received drops during initial attack. Our results confirm earlier work suggesting extensive use of large airtankers on extended attack, despite policy suggesting priority use in initial attack. Further, results suggest that containment rates for fires receiving large airtanker use during initial attack are quite low. We explore possible causes for these results, address potential limitations with our methods and data, and offer recommendations for improvements in data collection and aviation management.

Additional keywords: cost effectiveness, fire and aviation management.

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Introduction

Wildfire activity in the United States incurs substantial costs and losses, and presents challenges to federal, state, tribal and local agencies responsible for wildfire management. Suppression costs are a major concern for federal agencies in a time of austere budgets, and in particular for the US Forest Service (USFS), which is responsible for ~70% of federal wildfire management expenditure. Increasing wildfire activity and suppression costs have and may continue to lead to budgetary disruptions and reductions for non-fire programs, presenting a threat to the fiscal health of the agency (Calkin *et al.* 2005; Thompson *et al.* 2013*a*). For example, in 1991, fire management represented ~13% of the agency's budget, rising to 21% in 2000, with 2012 expenditure of ~50%. The additional socioeconomic and ecological losses due to wildfire are difficult to calculate in financial terms (Venn and Calkin 2011), although in some cases they have been estimated to exceed suppression costs by between two and 30 times (Western Forestry Leadership Coalition 2009). An additional cost of wildfire management is that it is a dangerous occupation. Between 2000 and 2012, 92 federal wildland firefighters died in the line of duty, averaging seven fatalities per year (USDI and USDA 2010; NWCG 2011, 2012*a*). Of these fatalities, 51% were associated with aviation accidents (USDI and USDA 2010; NWCG 2011, 2012*a*).

Large airtankers (LATs) that drop chemical retardant to suppress fire growth are one of the most iconic symbols of wildland fire. Aviation resources as a whole play a critical role in wildfire management and typically account for ~25% of suppression-related costs for the Forest Service (Table 1). Cost effectiveness has been established as the measurement criterion for fleet design (USDA Forest Service 2012), but the current state of data acquisition and management cannot support a rigorous cost-effectiveness analysis (Thompson *et al.* 2013*b*). A necessary first step towards estimating cost effectiveness is establishing an understanding of LAT usage in the wildland fire environment. If current usage is directed primarily towards initial attack (IA), cost-effectiveness analyses can focus on how LATs improve the likelihood of successful containment.

Table 1. US Forest Service aviation costs and costs for large (LAT) and very large airtankers (VLAT) in relation to total suppression expenditure, 2007–2011

Year	Aviation cost	LAT and VLAT cost	Total suppression cost	Percentage aviation	Percentage LAT aviation
2007	$355 600 000	$41 098 034	$1 373 919 000	25.9	11.6
2008	$367 500 000	$64 275 088	$1 458 805 000	25.2	17.5
2009	$286 600 000	$56 324 005	$1 018 329 372	28.1	19.7
2010	$252 900 000	$54 918 346	$897 686 406	28.2	21.7
2011	$353 300 000	$67 714 174	$1 414 379 757	25.0	19.2
5-year total	$1 615 900 000	$284 329 647	$6 163 119 535	26.2[A]	17.6[A]

[A] Value is a 5-year average.

IA incidents are generally fully controlled within the first burning period (NWCG 2012*b*), and LATs are generally thought to be most effective during IA, due to their ability to quickly reach a fire and prevent or inhibit spread before the fire can grow large (e.g. Plucinski *et al.* 2007; Ganewatta and Handmer 2009). LAT usage also occurs after the initial burning period during extended attack (EA) for a range of objectives including building line, slowing fire spread and point protection. If LATs are used extensively during EA, more complicated metrics that require understanding their marginal contribution to reducing wildfire damage will be required. Working towards achieving a cost-effective fleet design, we utilise spatially explicit retardant drop location data to expand on previous efforts such as Thompson *et al.* (2013*b*) to understand the distribution of LAT use on IA *v.* EA and provide an assessment of the effectiveness of LATs during IA use.

US fire management agencies do not own LATs, but have historically relied on private vendors to provide a fleet of LATs to meet suppression demands through a system of annual 'exclusive use' contracts guaranteeing rates for flight hours and daily use for specified aircraft and a fixed number of days. 'Call when needed' agreements allow the USFS to utilise additional private, state-contracted, Canadian, or military aircraft in a surge capacity and at generally higher use cost, given that these aircraft are available when needed. The agency must weigh the annual costs of maintaining a sizeable 'exclusive use' fleet to meet potential wildfire protection needs during active fire seasons against the probability of overinvesting during mild and moderate fire seasons.

Since 2002, the fleet of USFS LATs on exclusive use contracts has experienced substantial challenges and change. In response to two fatal LAT accidents in 2002, the federal government commissioned a report on aerial firefighting safety and effectiveness. The report identified a series of key problems, including the unacceptable safety record of aircraft, and that organisational, structural and managerial factors could compromise the safety and effectiveness of wildland fire management (Blue Ribbon Panel 2002). In response, in 2004 agency officials cancelled the contracts for the entire fleet of 33 exclusive use LATs due to concerns over airworthiness (Rey and Scarlett 2004). Table 2 illustrates the history of the USFS contract fleet of LATs since 2002, along with descriptions of accidents of associated aircraft and other major factors that reduced the fleet size over time. Due to the depletion of the LAT fleet, the USFS and the US Department of Interior (USDI) released an airtanker modernisation strategy and commissioned studies to explore appropriate fleet designs (USDA Forest Service 2012). The modernisation strategy highlighted cost effectiveness as the fundamental tenet of both the replacement strategy and the use of aerial firefighting resources. However, determining the cost effectiveness of alternative airtanker fleets is challenging due to limited data and substantial uncertainty regarding aerial firefighting effectiveness (GAO 2007; OIG 2009).

The effectiveness of suppression efforts in containing wildfires is relatively poorly understood, particularly on large wildfires (Finney *et al.* 2009). Dynamic fuel and weather conditions interact with topography, natural and manmade barriers to fire spread, human factors that determine suppression strategies, and interaction among different types of suppression resources are all elements that present considerable analytical challenges with respect to predicting fire spread (Finney *et al.* 2011; Holmes and Calkin 2013; Wibbenmeyer *et al.* 2013). Looking more broadly, we have only a limited ability to describe the return on suppression investment because quantifying the benefits of suppression effort is a very complicated problem requiring counterfactual projections or data-intensive statistical analysis. Clearly, we can observe the effects of an individual fire event, but our ability to predict how these consequences would have changed in the absence of a specific suppression action is extremely limited. For example, an individual drop from a LAT on a large fire event might have delayed fire spread in such a way that significant highly damaging events, or even fatalities, may have been avoided. Under many circumstances, we are unable to distinguish such a drop from one that had little to no net effect on final wildfire outcomes, due to the complex interactions identified above.

Thompson *et al.* (2013*b*) assessed the availability and sufficiency of data as a prerequisite for a cost-effectiveness analysis of LAT use in the United States. The authors reviewed LAT usage and cost trends from 1993 to 2010 and summarised flights according to mission type and fire size class for 2007–2010. Due to data limitations, they were only able to show that somewhere between 6.6 and 48.1% of overall flights were used for IA. A key recommendation to come from Thompson *et al.* (2013*b*) was a need for improved data collection and reporting standards – specifically, the ability to track drop location and time, to associate drops to specific fire events, to gather information on the fire environment (fuels, weather, terrain, etc.) at the time of the drop and, critically, to clearly identify mission objectives for each drop. Even with the lack of specificity afforded by the data, the 51.9 to 93.4% of use on EA does not support prior agency statements that the priority for LAT use is IA (USDA Forest Service 2011*a*).

Table 2. The 10-year history (2002–2012) of the US federal fire suppression large airtanker (LAT) fleet, including contract fleet size and notable events and accidents of associated aircraft

Year	Contract fleet size	Event date	Tanker model	Tanker number	Tanker owner	Event description
2002	44	Early season				Annual reported contract number (P. Linse, pers. comm., 2012)
	43	17-Jun-02	C-130A	T130	Hawkins & Powers	Accident during retardant drop due to major structural failure, three fatalities (USDA Forest Service 2002)
	42	18-Jul-02	PB4Y-2	T123	Hawkins & Powers	Accident during retardant drop due to major structural failure, two fatalities (USDA Forest Service 2002)
2003	33	26-Mar-03	C-130A & PB4-Y			USFS and BLM decline to renew contracts for nine C-130A and PB4-Y tankers (Hamilton 2003) following findings of Blue Ribbon Panel (2002)
2004	33	Early season				Annual reported contract number (P. Linse, pers. comm., 2012)
	0	10-May-04				USFS terminates contracts for entire LAT fleet due to airworthiness concerns (USDI and USDA 2004*a*)
	5	02-Jul-04	P-3 Orion			USFS returns five P-3 Orions to service (NIFC 2004)
	7	02-Jul-04–12-Aug-04	P-3 Orion			Two more P-3 Orions return to service some time during this period
	9	12-Aug-04	P2V			Two P2Vs also return to limited firefighting service (USDI and USDA 2004*b*)
2005	8	Early season	P-3 Orion			P-3 Orions from prior season returned to service with one DC-7 on restricted use (USDI and USDA 2005)
	7	20-Apr-05	P-3 Orion	T26	Aero Union	Accident during training mission, training plane, three fatalities (USDA Forest Service 2005)
	17	26-May-05	P2V			Announced that nine P2Vs to return to service this season following documentation of maintenance and total flight hours (USDI and USDA 2005)
2006	18	Early season				Annual reported contract number (P. Linse, pers. comm., 2012)
2007	19	Early season				Annual reported contract number (P. Linse, pers. comm., 2012)
2008	19	01-Sep-08	P2V	T09	Neptune	Accident during takeoff while on a fire, state contract LAT, three fatalities (USDA Forest Service 2008)
2009	19	Early season				Annual reported contract number (P. Linse, pers. comm., 2012)
	18	25-Apr-09	P2V	T42	Neptune	Accident during ferry flight, three fatalities (USDA Forest Service 2009)
2010	19	Early season				Annual reported contract number (P. Linse, pers. comm., 2012)
	18	26-Jun-10	P2V	T44	Neptune	Accident due to brake loss during landing, no fatalities (USDA Forest Service 2010)
2011	19	Pre-season	P2V	T44	Neptune	T44 repaired and returned to service for contract year 2011 (Gabbert 2010)
	17	15-Apr-11	P-3 Orion		Minden	Eight P-3 tankers grounded temporarily for emergency inspections, six return to service (Gabbert 2011)
	11	29-Jul-11	P-3 Orion		Aero Union	USFS terminates Aero Union contract for P-3 Orions, six in use pulled from service (USDA Forest Service 2011*b*)
	12	23-Sep-11	BAe-146	T40	Neptune	First next-generation tanker receives interim approval from Interagency Airtanker Board (Chaney 2011)
2012	11	Pre-season	P2V	T10	Neptune	T10 grounded pre-season due to crack found in wing spar (FAA 2012)
	10	03-Jun-12	P2V	T11	Neptune	Accident during retardant drop on a fire, two fatalities (Gabbert 2012)
	9	03-Jun-12	P2V	T55	Minden	Accident due to failed deployment of landing gear results in hard landing, no fatalities (Gabbert 2012)
	9	01-Jul-12	C-130	MAFFS 7	US Air Force	Accident while approaching intended drop zone, four fatalities, two injuries (USAF 2012)
	10	01-Sep-12	BAe-146	T41	Neptune	Second next-generation tanker brought on contract under interim approval (Chaney 2012)

The extensive use of LATs beyond IA poses many challenges in evaluating cost-effective fleet design. Thompson *et al.* (2013*b*) provide a thorough review of relevant aerial firefighting studies as well as modelling challenges, so here we will focus on a few particularly salient points. First, although models of IA are fairly well developed and extensively used (e.g. Fried and Fried 1996; Fried *et al.* 2006), models of large fire suppression are much rarer and much more difficult to parameterise and calibrate. Second, in cases where large fire suppression efforts are modelled (e.g. Mees and Strauss 1992; Podur and Martell 2007), the rate of aerial fireline production is compared to the rate of fire spread, which cannot account for delayed rather than prevented spread, or for alternative uses of aviation resources such as point protection. Third and most critically, previously published studies purporting to derive optimal fleet designs (Fire Program Solutions 2005; Keating *et al.* 2012) have based their analyses on IA being the predominant use of aerial resources, which we now know is not the case. One can quantify the benefits of LAT use in IA as the change in IA success rate multiplied by avoided negative consequences due to successful containment. Keating *et al.* (2012) introduced a useful conceptual framework of 'ABC' fires (not to be confused with established US federal fire size class definitions) for identifying where LATs can effect meaningful change in IA

Table 3. Aircraft use patterns on USFS fires from 1990 to 2011 using US Forest Service Fire Statistics System (FIRESTAT) fire occurrence records (http://www.fs.fed.us/fire/planning/nist/applicat.htm#FIRESTAT)

Year	Number of fire records	Percentage fires without aircraft	Percentage fires with any helicopter	Percentage fires with any airtanker	Percentage fires with both airtanker and helicopter
1990	11 992	89.8	5.9	2.6	1.8
1991	10 962	90.3	5.5	2.7	1.6
1992	11 776	89.5	6.2	2.2	2.1
1993	7916	91.1	5.6	1.6	1.7
1994	14 806	86.1	7.8	3.4	2.7
1995	9330	89.4	5.9	2.2	2.6
1996	11 605	84.5	9.0	3.1	3.4
1997	7967	87.0	8.8	1.5	2.7
1998	9505	84.0	11.5	1.8	2.7
1999	11 076	85.4	10.2	1.7	2.7
2000	11 089	80.2	14.3	2.1	3.5
2001	10 526	80.4	13.6	2.5	3.6
2002	9246	79.1	13.6	2.9	4.4
2003	10 064	78.1	16.1	2.0	3.8
2004	8348	81.5	14.2	1.5	2.7
2005	7355	81.1	13.3	2.1	3.5
2006	11 224	80.0	14.2	2.0	3.8
2007	9158	81.4	13.3	1.8	3.5
2008	7529	84.2	11.9	1.2	2.7
2009	7985	84.6	12.3	1.0	2.2
2010	7143	85.4	11.6	0.7	2.4
2011	7540	84.4	12.3	0.8	2.4
All Years	214 142	84.5	10.6	2.1	2.8

success. In this schema, Category A fires can be contained using only local resources, and LATs are unnecessary. B fires will only be contained if LATs are used, and C fires will escape IA and grow large irrespective of LAT use. Ideally, LATs would be sent only to Category B fires. Application of this schema is premised in part on the quality and timeliness of information available to fire dispatch systems but also on a prior ability to distinguish characteristics that would help appropriately categorise 'ABC' fires, which is difficult given the lack of empirically established information regarding factors that affect suppression effectiveness (Finney *et al.* 2009).

The benefits of LAT use in EA can be similarly defined. Success rate is essentially a function of the same variables, although success is not as easy to define when considering the broader range of drop objectives, including delaying rather than preventing spread, protecting vulnerable resources and assets, and enhancing firefighter safety. Uncertainty regarding how various environmental and operational factors contribute to attainment of these objectives is relatively high.

Supporting the conceptual ideas proposed by Keating *et al.* (2012), USFS Fire Statistics System (FIRESTAT) records provide a general picture of both aircraft usage trends and the relationship between aircraft use and final fire size class. From 1990–2011 the percentage of USFS fires not utilising aircraft during IA remained constant (Table 3). From 1990–2011, 84.5% of all fires had no aircraft support during the initial suppression response. Of the 15.5% with IA aircraft support, helicopters and airtankers were ordered 88% and 31% of the time (Table 3). During this same period, only 9% of fire size Class A fires (<0.10 ha) received any aircraft support, compared to 54% of fire size Class D–G fires (>40 ha; Fig. 1), suggesting that aircraft were ordered more often for difficult-to-suppress fires than for smaller, perhaps more easily controlled, fires. FIRESTAT data do not provide insight regarding timing of aircraft use and the respective fire size so we cannot use these data to determine whether aircraft associated with larger fires (Class D–G) were utilised early on when the fires were still small.

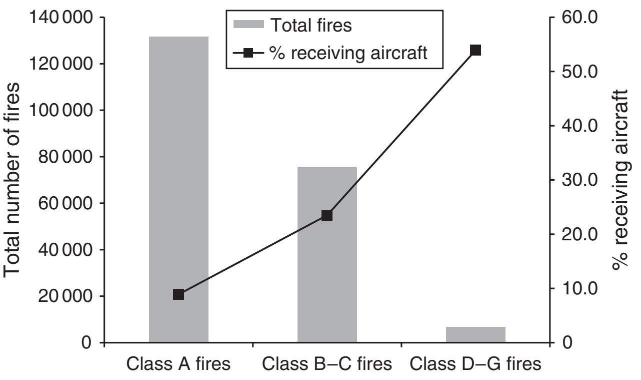

Fig. 1. Aircraft use in initial suppression response and corresponding final reported fire size class for 1990–2011 as reported in US Forest Service Fire Statistics System (FIRESTAT) records (http://www.fs.fed.us/fire/planning/nist/applicat.htm#FIRESTAT).

In this manuscript, we work towards a cost-effectiveness analysis of the large airtanker fleet by expanding on Thompson *et al.* (2013*b*). Specifically we (1) incorporate spatially explicit retardant drop location data, (2) extend the analysis to better capture the period in the fire history when the drop occurred (IA or EA) and (3) characterise the outcome of those fires that received drops during the IA period, using the metric of the proportion of fires that received retardant drops during IA that ultimately escaped. The methods described here allow us to clearly identify use in IA *v*. EA and fire outcome if the use was during IA. Containment success in IA is one reasonable measure of effectiveness, particularly if you can identify whether or not the fire would have escaped in the absence of LAT (Category B fire, Keating *et al.* 2012). If a high proportion of use occurs during EA (shown here and by Thompson *et al.* 2013*b*) then substantially more work needs to be done to allow us to make statements regarding effectiveness (e.g. mission objective) before we can make a rudimentary cost-effectiveness argument and subsequently design a cost-effective fleet and fleet management systems.

Methods

Data sources and characteristics

The Operational Loads Monitoring Systems (OLMS) installed onboard the USFS-contracted LAT fleet utilise digital sensors that log flight parameters (airspeed, heading, elevation, etc.) and door action on the retardant bay, indicating a retardant 'drop'. These drop occurrence data are tagged with timestamps and geospatial coordinates, and provide comprehensive documentation of spatial and temporal characteristics of the majority of LAT use in fire suppression on a national scale for the conterminous US. Due to data availability issues, we restrict our analysis to 2010 and 2011. The data indicate drops from the contract fleet only, consisting of 19 Type 2 tankers in 2010 and 10 in 2011. Therefore, this analysis excludes drop data from 'call when needed' aircraft, including the very large airtankers (VLAT) and C-130 military cargo planes outfitted with Modular Airborne Firefighting Systems (MAFFS). Expanded future analyses could potentially incorporate these data to provide a more comprehensive picture of large airtanker use.

The raw OLMS data do not include information regarding mission or wildfire incident, thus for analysis of patterns-of-use we must first manually link drops to unique fires. Due to the often-clustered nature of fire starts, it is not accurate to simply assume that a drop record will be associated with the closest fire with a start date similar to and preceding the drop date. In addition, the consistency and quality of fire records varies widely among data sources, and no single dataset provides a complete and accurate record of all fire start locations across all ownerships. To accurately match drop records to unique incidents we integrated multiple datasets. First, we compared spatial and temporal drop parameters with several fire location datasets, including FIRESTAT, SitReport, FireCode, Wildland Fire Decision Support System (WFDSS), GeoMAC and state fire records. Then, we used this collection of fire history data in conjunction with resource tracking data to determine which fires utilised LAT support.

The National Interagency Resource Ordering Status System (ROSS) is a dispatch program that tracks ordering and distribution of tactical, logistical, service and support resources – like LATs – to incidents across the country. The system's ability to identify requests for specific resources allows tracking of the duration and timing of resource assignments to an incident. While useful, the ROSS requests do not provide a complete picture of use. Resources are sometimes shared between incidents, especially if there is a cluster of fire starts involving the same host unit. An LAT ordered for a single incident may actually deliver retardant to multiple small fires, but there may only be a single ROSS request for the ordering fire. Moreover, a filled ROSS order for an LAT does not guarantee retardant delivery. A plane may be assigned to an incident then grounded at an airport due to poor flying conditions. It may subsequently be released and assigned to another incident without ever making drops on the first fire.

Automated Flight Following (AFF) data help address the deficiencies in the ROSS dataset for matching OLMS drops to fires. These data are available for the entire fleet of contracted LATs, and provide spatial tracking and flight data (airspeed, elevation, heading, etc.) for aircraft locations with a new geospatial coordinate every few minutes. Comparison of these data with the filled ROSS records enables assessment of whether an airtanker flew in the assigned fire's vicinity during the period for which it was assigned to that fire. Additionally, drop records that closely align with geospatial fire perimeter or location data with no corresponding ROSS request for LATs can sometimes be logically assigned using these AFF data.

Examination of ROSS requests and AFF data still leaves a small number of OLMS drops that cannot be clearly matched to a fire. Ancillary data sources, like archived media footage and fire information websites (e.g. InciWeb.org, wildlandfire.com), provided further information on spatial fire locations, particularly for small, short-duration wildfires receiving a single retardant drop. Table 4 summarises the characteristics of these data sources.

Matching retardant delivery data to unique fire incidents

Due to inconsistencies in incident data collection and management, the process of matching OLMS drop records to individual wildfire incidents is entirely manual. First, all available fire perimeter data are displayed in a geographic information system, along with geospatial drop records labelled by local time at drop. Clear associations are made for those drops that spatially and temporally match fire perimeters, and the drop record dataset is populated with new fields detailing the incident name and the associated Unique Fire Identifier (Fire ID: a unique number assigned to each fire reflecting the discovery year, the state and host unit of the fire origin, and the local fire number; NWCG 2007).

Next, unmatched drops are displayed on a map alongside dated fire location data (in absence of perimeter data). A ROSS report listing all LAT requests filled by the federal fleet for the year of interest is used with the AFF and fire location data to help match the remaining drops to fires. Drops with spatial and temporal correlation to fire locations and start dates, as well as with corresponding ROSS requests for LATs, are associated with those incidents using the incident name and Fire ID fields. Ancillary data sources are used, where possible, to make fire associations for the final uncategorised drop records.

The drop records that cannot be matched to a fire are classified as either 'false positive' or 'unknown'. False positives can occur with excessive vibration due to turbulence or flight manoeuvres, with sensor malfunction, when pilots re-cycle the doors following a drop, and when drops are recorded during training or jettison missions. This designation is reserved only

Table 4. Overview of data sources used in analysis of airtanker use in federal fire suppression

Data source	Data name	Information provided	Limitations	Reference
OLMS	Operational Loads Monitoring Systems	Retardant drop locations, times and flight parameters for contract fleet	Not inherently linked to incidents or flight objectives Not all large airtanker (LAT) drops are captured	Missoula Technology and Development Center and US Fire and Aviation Management, unpublished raw data
AFF	Automated Flight Following	Flight path locations, heading, elevation and airspeed	Overwhelming data volume	Missoula Technology and Development Center and US Fire and Aviation Management, unpublished raw data
ROSS	Resource Order and Status System	Requests for nationally dispatched resources	Resource sharing between incidents Filled order does not guarantee LAT use	https://rossreports.nwcg.gov
FIRESTAT	Fire Statistics System	Fire location data	Incomplete records of fire occurrence across the conterminous United States (CONUS) and for all ownerships	National Fire and Aviation Management Web Applications (FAMWEB) https://fam.nwcg.gov/fam-web/
SitReport	Incident Management Situation Report	Fire location data	Incomplete records of fire occurrence across the CONUS and for all ownerships	FAMWEB
FireCode	Fire Code	Fire location data	Incomplete records of fire occurrence across the CONUS and for all ownerships	https://www.firecode.gov
GeoMAC	Geospatial Multi-Agency Coordination Group	Fire perimeter data	Incomplete records of fire occurrence across the CONUS and for all ownerships	www.geomac.gov
WFDSS	Wildland Fire Decision Support System	Fire location, perimeter and size data	Incomplete records of fire occurrence across the CONUS and for all ownerships	https://wfdss.usgs.gov
ABS	Aviation Business System	Aviation costs	Use of miscellaneous fire codes to pay aviation costs complicates directly matching ABS records to incidents with LAT use	FAMWEB
Miscellaneous Ancillary	Inciweb; wildlandfire.com Initial attack forum; archived media footage and news clips	Generally, fire location and timing for initial attack incidents that are quickly contained	Lack of consistency in data sources introduces questions of data reliability	www.Inciweb.org; www.wlfhotlist.com misc. Internet sites

for those records where it was abundantly clear that the drop records were not indicative of potential use on wildfire suppression. ‘Unknown’ drops could be real drops on an actual fire or they could be false positives. Either way, there is enough ambiguity surrounding these data that we cannot confidently assume they are not real drops.

The current system of OLMS data acquisition relies on both properly functioning and installed sensors and cooperation with LAT vendors to physically deliver the data to the appropriate USFS entity. While comprehensive, the 2010 and 2011 dataset is not complete due to both factors mentioned here. To assess the quality and quantity of the missing drop data, filled ROSS requests and AFF data were further analysed to identify fire locations where it was highly likely that one or more drops occurred, but where no drop data were reported. These associations were made by assessing where the LAT was assigned, where it flew, and specifically how it flew. If an LAT flew in the vicinity of an assigned fire during the period of assignment, and it displayed characteristic flight patterns of retardant delivery (low elevation and slow flight speed at the time of the drop associated with subsequent changes in flight heading), then a record was created in the OLMS dataset detailing the location of missing drops associated with a specific fire. The number of missing drops was not assumed and these data were not included in further analysis. This process was completed to assess the distribution of these missing drops across time and space, to identify potential issues in the sample caused by the missing records.

This close examination of AFF, ROSS and OLMS data also revealed instances where airtankers were not directly ordered in ROSS, but where the patterns of flight coupled with an unmatched lone drop record were highly suggestive of miscellaneous IA. These drop records were classified as ‘miscellaneous IA’ and may have been associated with ROSS requests utilising miscellaneous fire payment codes (ABCD codes), miscellaneous IA, or they may represent further examples of resource sharing between incidents.

Response and containment classification

Once drops were matched to unique fires, the OLMS drop records were then categorised according to time of response (IA *v.* EA) and containment (contained *v.* escaped) definitions. Response refers to the use of LATs during a certain phase of

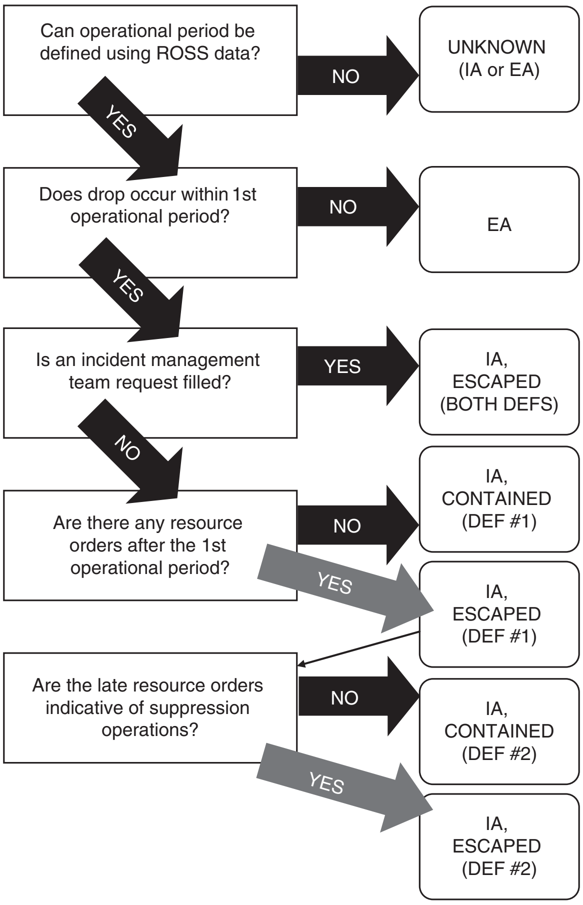

Fig. 2. Decision tree for tiered initial attack (IA) and extended attack (EA) classification of retardant drops and incident containment outcome. Resource Order and Status System (ROSS) resource requests are used to identify whether suppression actions occur during IA or EA periods and whether these actions resulted in a contained incident. Two potential definitions for incident containment are possible. Definition 1 is fully objective but results in overestimation of escaped incidents due to late supply and mop-up resource orders occurring for fires effectively contained during the first operational period. Definition 2 more accurately identifies contained incidents but introduces a level of subjectivity in the classification process.

suppression, either during IA or EA, and containment assesses whether the suppression actions appear to have stopped the fire during the IA phase. For all analyses, this classification relies on ROSS resource order data to establish a timeline of events. In the absence of ROSS data matching the incident of interest, the drops remain unclassified.

The operational start is defined here as the date and time of the first ROSS request for resources of any kind. The first operational period is thereafter defined as the first 24 h following the operational start. Drops within the first operational period are classified as IA; drops after that point are called EA.

Fig. 2 illustrates the decision tree for a tiered IA containment classification scheme, which was devised to capture a potential range of containment definitions. The ROSS program categorises all resource orders into one of the following groups: aircraft, crews, equipment, overhead and supply. This classification is used in the containment definition criteria. Definition 1 is the most stringent. For those fires with only IA drops, an incident is classified as 'escaped' using Definition 1 if any ROSS request is placed after the first operational period. This approach is completely objective but will overestimate IA use leading to escaped incidents because supply orders to restock a fire cache or replace broken items often occur in the days or weeks following a fire. Additionally, resources ordered for mop-up operations on the second day could inaccurately suggest an escaped incident. Definition 2 addresses this issue through a more subjective definition. Using the same process for IA fires, only certain resources that are indicative of suppression and ordered after the first operational period signify an escaped incident. For example, an IA incident with only supply orders after the 24-h cutoff would be classified as 'contained' using the Definition 2 criteria. For both definitions, any incident that also has a Type I or II incident management team assigned is automatically classified as escaped because this suggests a level of complexity and long-term management that is not consistent with an incident contained during the IA phase. Fires with drops during and after the IA cutoff are classified as escaped, and fires with drops only during EA do not receive a containment classification because they are only used after IA containment has failed. Categorisation of the data using the two containment definitions did not produce dramatically different results, and as expected, Definition 1 predicted a higher level of escaped incidents. After reviewing thousands of ROSS requests and becoming familiar with the patterns of resource ordering related to actual on-the-ground fire operations, from our point of view, Definition 2 most accurately aligns the incidents with known outcomes. All further analyses presented in this paper will utilise the Definition 2 containment criteria depicted in Fig. 2.

In addition to understanding patterns of use associated with individual drop records, it was useful to further classify the data by response and containment with respect to individual incidents. A list of all incidents with associated drops is classified in the same manner as for individual drops. Because individual incidents may receive drops during both IA and EA, an additional classification was created to properly distinguish this situation ('IA/EA').

Finally, in order to assess the quality of the response and containment definitions utilised in this analysis, ROSS resource orders associated with LAT fires were examined to identify the average date of demobilisation of all resources with respect to the initial fire date as reported in ROSS. The results demonstrated logical patterns supporting our definition criteria, namely that contained IA incidents dominated the frequency distribution in the <1-day and 1–2-day categories, escaped IA and IA/EA fires were found in the middle of the distribution, and EA-only fires tended to demobilise resources after the greatest period of time from the start of the fire. An analysis of fire size class distribution by response and containment categories followed the same expected patterns. The results of these sub-analyses are not presented in this paper but can be obtained from the authors upon request.

Results

Table 5 provides OLMS data summaries for 2010 and 2011. The former was a mild fire year across the conterminous US. A total 2448 drop records were tied to 307 different incidents, with three

Table 5. Operational Loads Monitoring Systems (OLMS) retardant drop record summary for calendar years 2010 and 2011

Response actions are defined as initial attack (IA) if they occur within 24 h of the first request for national resources. Texas data are singled out because Texas incidents tended to follow different airtanker ordering protocols, and therefore, the drops could not be classified IA using the same classification schema devised for the rest of the country

Statistics	Year	
	2010	2011
Total drops	2448	3290
Unique incidents	307	327
Unknown drops	40 (1.6%)	120 (3.6%)
Miscellaneous IA drops	17 (0.7%)	12 (0.4%)
Texas drops	49 (2.0%)	900 (27.4%)
Texas incidents	2	98
Drops by incident statistics		
Median	3	4
Mean	7.8	9.7
Standard deviation	12.8	17.5
Skewness	4.5	4.6

median drops per fire. Another 40 drops could not be assigned to an incident (unknown) and 17 were associated with miscellaneous IA use that was not tied to a specific ROSS LAT request. In 2011 there was increased fire activity, particularly for the South-west US and the state of Texas. Although the fleet size shrank to 10 planes for part of 2011 from 19 planes in 2010 (Table 2), the sample size increased to 3290 drop records. These drops were tied to 327 unique incidents with four median drops per incident. A total 120 drops were categorised as unknown and 12 drops were assigned to miscellaneous IA. A notable difference in the two calendar year samples is the increase in LAT use in Texas for 2011. Only 49 drops were reported from two separate Texas incidents in 2010. In contrast, for 2011, 900 drops or 27.4% of the total sample came from Texas drops associated with 98 separate incidents.

Fig. 3 presents frequency distributions for the two sample years, as well as national maps showing fire locations with graduated symbols representing increasing number of LAT drops by symbol size. The distributions for both years are highly skewed to the right (skewness >4.5); however, 2011 has a greater number of extreme outliers representing large fire support or EA-type incidents that saw heavy LAT use. In 2010, there is one fire nationally with more than 75 total drops, compared to six fires in 2011 in this category.

Response and containment results

Table 6 summarises the annual drop data by response (IA *v.* EA) and containment (contained *v.* escaped). This analysis led to an interesting discovery concerning resource-ordering patterns in Texas. It is a ROSS business rule that large airtankers are released by an assigned incident at the end of each operational period, thereby freeing that resource for national availability the next day (NIFC 2005). This pattern of use is observed consistently across the county, with the exception of Texas. Despite the level of heavy LAT use in 2011 in Texas (27.4% of all drops), there were just 87 filled requests for contracted LATs associated with only four unique incidents. Furthermore, tankers were mobilised per ordering incident for an average of 6.4 days, with some LATs assigned to an incident for more than 30 days at a time. The response and containment model described here does not hold up under these conditions of multi-day use because it relies on the ROSS resource order records to establish both a timeline of fire suppression actions and subsequent containment outcomes. Multi-day LAT assignments are inconsistent with national LAT use with respect to ROSS ordering patterns; therefore, we removed Texas drop data from the sample for the purposes of response and containment analyses.

Table 6 provides the data breakdown for all drops by calendar year, excluding Texas. The data are first summarised by individual drop record. In 2010, 63.4% of all drops were within the first operational period (IA), while 34.4% of all drops were used in EA operations. In 2011, 43.3% of drops were used on IA and 50.9% of drops were used in EA.

The drop data were also summarised to capture the response and containment characteristics of individual fires that received LAT support. Table 6 displays the annual count of individual fires in each response and containment category. This method of summarisation shows a higher proportion of fires where LATs were used solely on IA (81.6% in 2010 and 63.3% in 2011); however, these figures are not indicative of total volume of LAT use. For example, the average number of drops per incident for IA-only fires, regardless of containment outcome, is 4.3 drops. Conversely, IA–EA fires (IA use leading to EA use) and EA-only fires see an average of 22.9 drops per incident. While these incidents comprise a smaller percentage of the number of individual fires receiving LAT support, they account for the bulk of LAT utilisation by drop number due to the heavy LAT use that these types of 'large fire support' EA events tend to see once LATs have been committed. In the US, a 'large fire' is defined for statistical purposes as any fire exceeding 121 ha (300 acres) in size (NWCG 2012*b*).

The containment classification of drops conducted during IA by sample year and as a cumulative total broken down by Geographic Coordination Area (GCA) is shown in Fig. 4. Most strikingly, IA use is associated with incidents that escaped IA the majority of the time for both sample years. Of the 1522 IA drops in 2010, 67.4% were associated with fires that escaped IA. In 2011, there were just 1036 IA drops, 84.8% of which were on fires that escaped. The average between the two sample years is 23.6% for IA use on contained fires, 74.5% on escaped incidents and 1.9% on incidents with an unknown containment outcome. Fig. 4 breaks down the results into GCAs. The Eastern Area is the only GCA where IA drops are associated with proportionally more contained incidents (62.3%) than escaped incidents (37.7%). The Northern and Southern California GCAs exhibit the next highest association between IA use and containment with containment rates of 37.1 and 33.1%. Conversely, the Northern Rockies, North-west and South-west GCAs show the greatest association between IA use and escaped incidents with escaped rates for IA drops exceeding 80%. The South-west Area dominates the total number of drops, with the Eastern Great Basin and the Southern California Areas not far behind with respect to total volume of LAT use. Predictably, given the comparative amount of fire on the landscape, the Eastern and Southern Areas saw the fewest number of cumulative LAT drops in the two sample years.

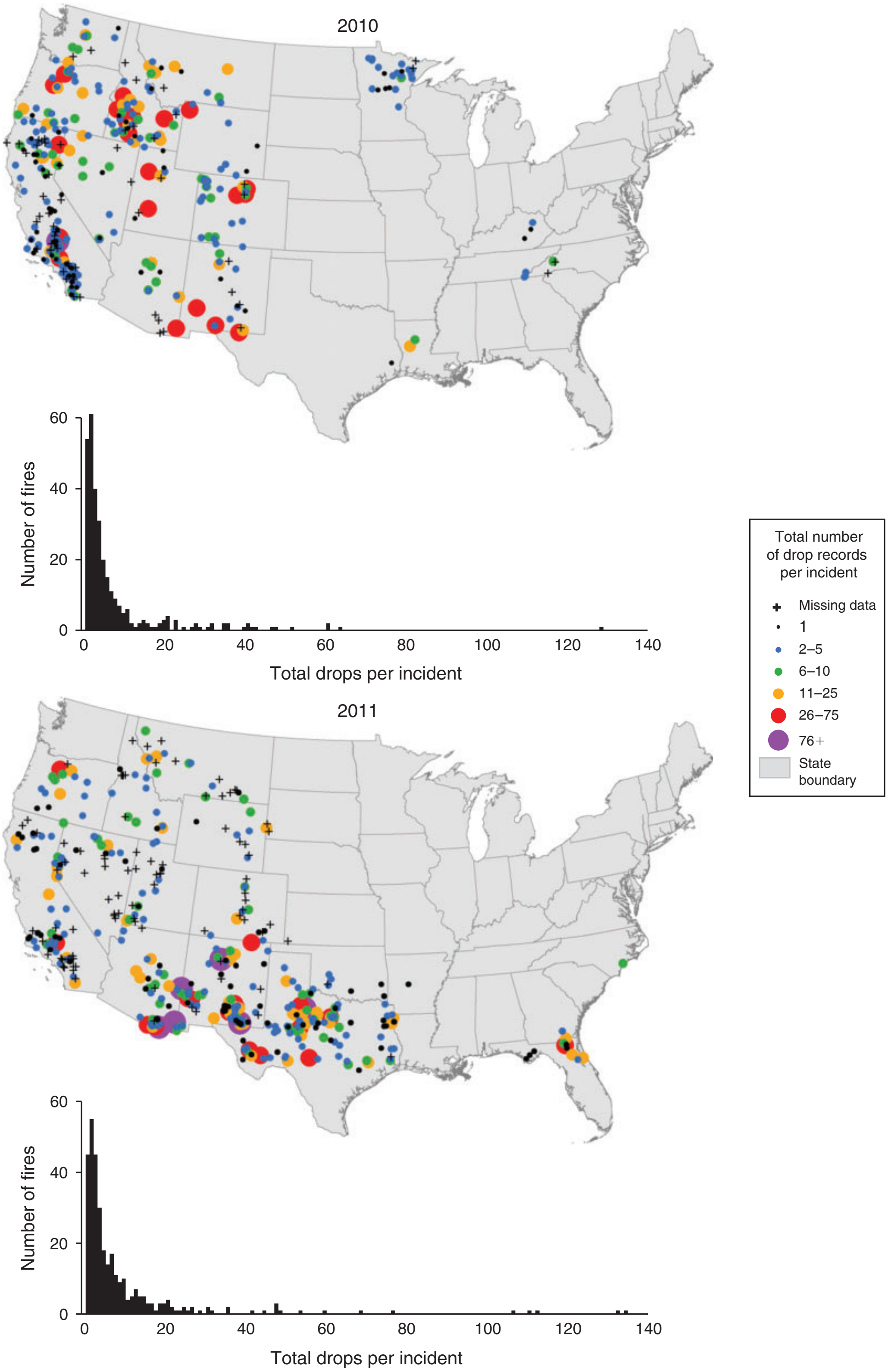

Fig. 3. Summary of the distribution of total number of retardant drops by unique incident for 2010 and 2011 from Onboard Load Monitoring Systems (OLMS) sensors for the majority of the US federally contracted large airtanker fleet. The maps show the total number of drops per fire by graduated symbol size and the graphs show the frequency distributions for the total number of drops by fire. Missing data points indicate incidents where Automated Flight Following (AFF) and Resource Order and Status System (ROSS) data suggest that at least one drop occurred but where these drop records are missing in the OLMS dataset.

Table 6. Response and containment summary by calendar year (2010 and 2011) using containment Definition 2 criteria, for all conterminous national drop data (without Texas), including analysis by individual drop record and by unique wildfire incident

Response actions are defined as initial attack (IA) if they occur within 24 h of the first request for national resources. Extended attack (EA) actions occur afterward. Fires are contained using the Definition 2 criteria if no incident management team is assigned and if any requests for national resources occurring after the IA period are not indicative of suppression operations

Response category	Containment category	Response by drop – number of drops (percentage of total)		Response by fire – number of fires (percentage of total)	
		2010	2011	2010	2011
IA	Contained	447 (18.6%)	156 (6.5%)	127 (41.6%)	52 (22.7%)
	Escaped	1026 (42.8%)	879 (36.7%)	101 (33.1%)	92 (40.2%)
	Unknown	49 (2.0%)	1 (0.0%)	21 (6.9%)	1 (0.4%)
IA/EA	Escaped	N/A	N/A	39 (12.8%)	41 (17.9%)
EA	N/A	824 (34.4%)	1219 (50.9%)	15 (4.9%)	33 (14.4%)
Unknown	Unknown	53 (2.2%)	140 (5.8%)	2 (0.7%)	10 (4.4%)

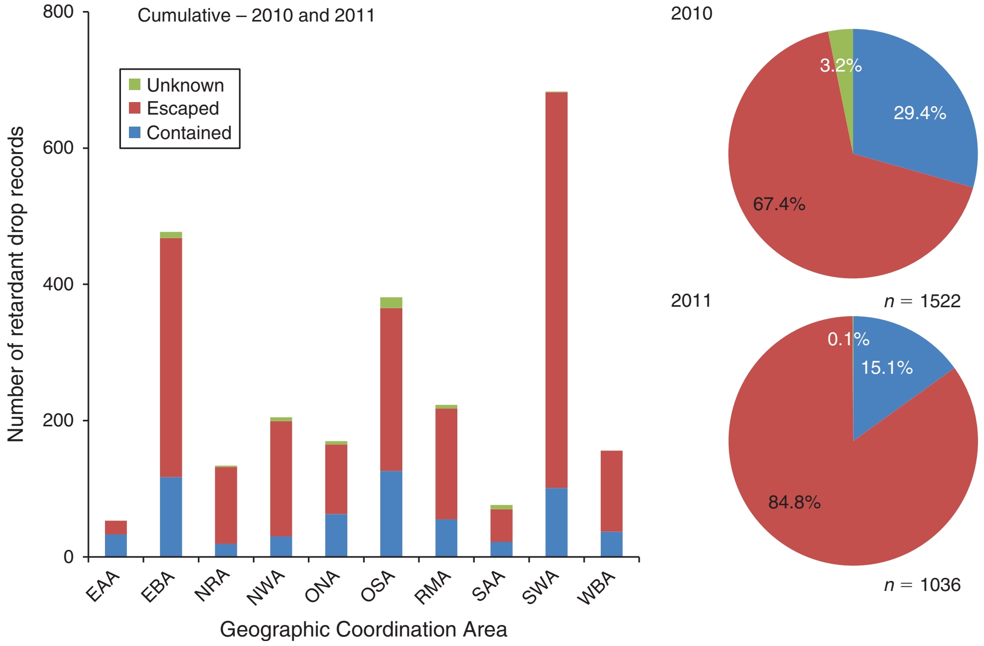

Fig. 4. Initial attack (IA) containment summary by year and cumulatively by US Geographic Coordination Area (GCA), including Eastern Area (EAA), Eastern Great Basin (EBA), Northern Rockies (NRA), North-west (NWA), Northern California (ONA), Southern California (OSA), Rocky Mountain (RMA), Southern (SAA), South-west (SWA) and Western Great Basin (WBA; http://gacc.nifc.gov/).

Discussion

These results confirm the findings of Thompson *et al.* (2013*b*) that a high proportion of LAT drops occur on EA fires. Additionally, we were able to identify that a large majority of LAT drops that occurred during IA in 2010 and 2011 were associated with fires that escaped. Compared to the 10-year average, 2010 was a notably quiet fire season (in terms of starts, escaped fires and acres burned), while 2011 was a more typical, but certainly not an extreme fire year, like 2012. Thus, our results will be somewhat limited in scope. Still, these results suggest that current LAT usage may not be consistent with stated policy. Under the current resource ordering system, IA and EA usage are considered of equal importance. Without expanded analysis of the effectiveness of LATs, we are unable to evaluate whether modification of LAT use to more closely match stated priorities would produce improved wildfire outcomes or greater resource use efficiencies. Nevertheless, this work greatly expanded our ability to spatially tie drops to fire events, to the status of suppression operations at the time of the drop and to final fire outcomes if drops occurred during IA operations. That the rate of escape associated with fires that receive drops during IA is so high – far higher than the general escape rate of approximately

2 to 5% – is strongly suggestive that LAT use, when it does occur in IA situations, occurs on the more difficult fires (i.e. Category C fires as defined by Keating *et al.* 2012).

From a modelling perspective, it may be more relevant to think of the Category B and C fires as a single class of fire that has a high escape potential. The determinant of escape relative to LAT use is simply the delay between ignition and the time of retardant drop, assuming that the availability and timing of ground resources remain constant. This is essentially how most IA models such as Fried *et al.* (2006) were developed, by comparing fireline production against fire perimeter growth. In the extreme, the most challenging Category C fire may be contained by LATs even in the absence of ground resources if the drop were to occur immediately after ignition (a highly unlikely scenario requiring perfect prescience of fire ignition location). Therefore, the determination of whether or not a fire will benefit from LAT drops in IA will be directly related to the delay from ignition to drop occurrence. This delay allows a fire to grow and cross a critical threshold where fireline production of IA resources cannot catch the growing fire perimeter. When evaluated in this light, the demonstrated low success rate for IA containment could be addressed by reducing the time between ignition and LAT arrival on these fires with a high potential to escape. This would require an improved ability to rapidly recognise an individual fire's escape potential so that LATs are ordered very early in the event. Further, this suggests that if we can improve our ability to identify when and where these types of ignitions are likely to occur we should be able to effectively pre-position LATs before an outbreak of fires. If the IA success rate could be improved through such a system, overall LAT demand may be reduced because many of the evaluated drops were associated with IA fires that ultimately escaped. However, implementation of such a system may also require moving LATs away from existing EA responsibilities to meet projected ignition pulses.

Earlier work by Keating *et al.* (2012) and others laid out an economic framework that attempts to identify a cost-effective fleet design to address US federal IA needs. However, the optimal number and type of aircraft in the cost-effective fleet are highly sensitive to baseline assumptions including the priority of LAT use in IA over EA, the relative effectiveness of water *v.* retardant, dispatch prescience, monetised avoided loss through IA containment and several other factors. To move towards cost-effective fleet design it will be necessary to address these assumptions and their surrounding uncertainties as well as to attain a better understanding of the contribution of LATs in achieving suppression objectives during EA. Another central tenet in developing cost-effective fleet design is the identification of conditions where LAT use is likely to be ineffective or unsafe, including a movement towards the commitment to restrict LAT use under these conditions. Key areas of future research working towards the goal of achieving a cost-effective fleet include (1) exploration of parameters affecting escape potential, including effects of LAT use in IA, (2) expansion of our ability to predict timing and location of pulses of fire activity to improve LAT pre-positioning, (3) improved national LAT pre-positioning models including implementation strategies and (4) improved understanding of socioeconomic and ecological consequences of escaped large fires to better quantify the benefits associated with IA containment.

The practice of wildfire management is complex and uncertain, which can lead to difficulties in analysing and interpreting firefighting effectiveness data, especially from an aviation-specific perspective. The greater flexibility in terms of location and allocation, and the larger role of ground resources in wildfire management may confound factors driving changes in outcomes from airtanker use. Nevertheless, our results confirm extensive LAT use in EA operations, suggest limited success in IA operations and point to a need to continue critical examination of the cost effectiveness of aviation practices. Investing in improved and expanded data collection systems and continued research represents tradeoffs among competing investments in wildfire management. However, without such investments, informed tradeoff analyses of alternative suppression organisations will remain elusive.

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References

Blue Ribbon Panel (2002) Federal aerial firefighting: assessing safety and effectiveness. Blue Ribbon Panel Report to the Chief, USDA Forest Service and Director, (USDI Bureau of Land Management) Available at http://www.wildlandfire.com/docs/2003_n_before/BRP_Final12052002-1.pdf [Verified 22 January 2013]

Calkin DE, Gebert KM, Jones JG, Neilson RP (2005) Forest Service large fire area burned and suppression expenditure trends, 1970–2002. *Journal of Forestry* **103**(4), 179–183.

Chaney R (2011) Neptune's jet-powered tanker could 'revolutionize' aerial firefighting. *Missoulian* 28 September 2011. Available at http://missoulian.com/news/local/neptune-s-jet-powered-tanker-could-revolutionize-aerial-firefighting/article_4cc0276e-ea4a-11e0-a4c5-001cc4c03286.html [Verified 22 January 2013]

Chaney R (2012) Neptune's 2nd jet-powered retardant bomber cleared to fly amid dispute. *Missoulian* 1 September 2012. Available at http://missoulian.com/news/local/neptune-s-nd-jet-powered-retardant-bomber-cleared-to-fly/article_370039be-f3e0-11e1-a1f1-0019bb2963f4.html [Verified 22 January 2013]

FAA (2012) Emergency airworthiness directive. (Federal Aviation Administration, Aviation Safety) Available at http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAD.nsf/0/6559a291129f39358625799c0064393c/$FILE/2012-03-51_Emergency.pdf [Verified 22 January 2013]

Finney MA, Grenfell IC, McHugh CW (2009) Modeling containment of large wildfires using generalized linear mixed-model analysis. *Forest Science* **55**(3), 249–255.

Finney MA, Grenfell IC, McHugh CW, Seli RC, Trethewey D, Stratton RD, Brittain S (2011) A method for ensemble wildland fire simulation. *Environmental Modeling and Assessment* **16**, 153–167. doi:10.1007/S10666-010-9241-3

Fire Program Solutions (2005) Wildland Fire Management Aerial Application Study. Available at http://www.fs.fed.us/fire/publications/aviation/nats3_wfmaas_report_final.pdf [Verified 22 January 2013]

Fried JS, Fried BD (1996) Simulating wildfire containment with realistic tactics. *Forest Science* **42**(3), 267–281.

Fried JS, Gilles JK, Spero J (2006) Analysing initial attack on wildland fires using stochastic simulation. *International Journal of Wildland Fire* **15**(1), 137–146. doi:10.1071/WF05027

Gabbert B (2010) Tanker 44 back in the air. *Wildfire Today*. Available at http://wildfiretoday.com/2010/12/07/tanker-44-back-in-the-air/ [Verified 22 January 2013]

Gabbert B (2011) 8 of the 19 heavy air tankers grounded. *Wildfire Today*. Available at http://wildfiretoday.com/2011/04/15/8-of-the-19-heavy-air-tankers-grounded/ [Verified 22 January 2013]

Gabbert B (2012) Two air tanker incidents, one crash and one wheels-up landing. *Wildfire Today*. Available at http://wildfiretoday.com/2012/06/03/two-air-tanker-incidents-one-crash-and-one-wheels-up-landing/ [Verified 22 January 2013]

Ganewatta G, Handmer J (2009) The cost-effectiveness of aerial firefighting in Australia. Bushfire Cooperative Research Centre, Technical report A.09.01. (Melbourne)

GAO (2007) Wildland fire management: lack of clear goals or a strategy hinders Federal Agencies' efforts to contain the costs of fighting fires. US Government Accountability Office, Report number GAO-07–655. Available at http://www.gao.gov/assets/270/261640.pdf [Verified 22 January 2013]

Hamilton L (2003) Testimony before Senate Energy and Natural Resources Committee at the Oversight Hearing concerning the Blue Ribbon Panel Report and aerial firefighting safety. Available at http://www.fs.fed.us/congress/108/senate/oversight/hamilton/032603.html [Verified 22 January 2013]

Holmes TP, Calkin DE (2013) Econometric analysis of fire suppression production functions for large wildland fires. *International Journal of Wildland Fire* **22**(2), 246–255. [Published online early 18 September 2012]. doi:10.1071/WF11098

Keating EG, Morral AR, Price CC, Woods D, Norton D, Panis C, Saltzman E, Sanchez R (2012) Air attack against wildfires: understanding US Forest Service requirements for large aircraft. (RAND Corporation) Available at http://www.rand.org/content/dam/rand/pubs/monographs/2012/RAND_MG1234.pdf [Verified 22 January 2013]

Mees R, Strauss D (1992) Allocating resources to large wildland fires: a model with stochastic production rates. *Forest Science* **38**(4), 842–853.

NIFC (2004) Limited number of large airtankers recalled to service. National Interagency Fire Center, NIFC News press release. Available at http://wildfirelessons.net/documents/airtankers_070204_NIFC_72DPI.pdf [Verified 22 January 2013]

NIFC (2005) Statement from the National Multi Agency Coordination Group regarding airtanker management and dispatch procedures. (National Interagency Fire Center) Available at http://www.nifc.gov/nicc/administrative/nmac/correspond/AT_mgmt_dsp.pdf [Verified 22 January 2013]

NWCG (2007) NWCG Data standard unique fire identifier discussion paper. Available at http://www.nwcg.gov/pmu/pmo-archive/products/stds/unique_fire_id/discussion.pdf [Verified 22 January 2013]

NWCG (2011) Safety Gram: fatalities, entrapments, and serious accident summary for 2011. (National Wildfire Coordinating Group Risk Management Committee) Available at http://www.nwcg.gov/branches/pre/rmc/safety-grams/sg_2011_f.pdf [Verified 14 January 2013]

NWCG (2012*a*) Safety Gram: fatalities, entrapments, and serious accident summary for 2012. (National Wildfire Coordinating Group Risk Management Committee) Available at http://www.nwcg.gov/branches/pre/rmc/safety-grams/sg_2012_d.pdf [Verified 14 January 2013]

NWCG (2012*b*) Glossary of wildland fire terminology. (National Wildfire Coordinating Group) Available at http://www.nwcg.gov/pms/pubs/glossary/index.htm [Verified 22 January 2013]

OIG (2009) Audit report: Forest Service's replacement plan for firefighting aerial resources. US Office of Inspector General, Report number 08601–53-SF. Available at http://www.usda.gov/oig/webdocs/08601-53-SF.pdf [Verified 22 January 2013]

Plucinski M, Gould J, McCarthy G, Hollis J (2007) The effectiveness and efficiency of aerial firefighting in Australia, Part 1. Bushfire CRC, Technical report A0701. (Melbourne)

Podur JJ, Martell DL (2007) A simulation model of the growth and suppression of large forest fires in Ontario. *International Journal of Wildland Fire* **16**(3), 285–294. doi:10.1071/WF06107

Rey M, Scarlett L (2004) Statement before Senate Commerce Committee concerning firefighting aircraft safety. Available at http://www.fs.fed.us/congress/108/senate/oversight/rey/060204.html [Verified 22 January 2013]

Thompson MP, Calkin DE, Finney MA, Gebert KM, Hand MS (2013*a*) A risk-based approach to wildland fire budgetary planning. *Forest Science* **59**(1), 63–77. doi:10.5849/FORSCI.09-124

Thompson MP, Calkin DE, Herynk J, McHugh CW, Short KC (2013*b*) Airtankers and wildfire management in the US Forest Service: examining data availability and exploring usage and cost trends. *International Journal of Wildland Fire* **22**(2), 223–233. [Published online early 10 August 2012]. doi:10.1071/WF11041

USAF (2012) United States Air Force Aircraft Accident Investigation Board Report regarding 1 July 2012 C-130H3 accident. Available at http://usaf.aib.law.af.mil/ExecSum2012/C-130H3_Edgemont_SD_1%20Jul%2012.pdf [Verified 22 January 2013]

USDA Forest Service (2002) FY 2002 aviation safety summary. National Aviation Safety Center (Boise, ID) Available at http://www.fs.fed.us/fire/av_safety/assurance/fy_safety_reports/fy02avsumm.pdf [Verified 22 January 2013]

USDA Forest Service (2005) Fire and aviation management briefing paper regarding agency airtanker program and recent Orion P-3 accident. Available at http://wildfirelessons.net/BrowseResults.aspx?All=61&New=0&Level=2&Value=280&Cat=61&Sub=0&Topic=0&Page=9 [Verified 22 January 2013]

USDA Forest Service (2008) FY 2008 aviation safety summary. National Aviation Safety Center. (Boise, ID) Available at http://www.fs.fed.us/fire/av_safety/assurance/fy_safety_reports/FY2008_Summary.pdf [Verified 22 January 2013]

USDA Forest Service (2009) FY 2009 aviation safety summary. National Aviation Safety Center. (Boise, ID) Available at http://www.fs.fed.us/fire/av_safety/assurance/fy_safety_reports/FY2009_Summary.pdf [Verified 22 January 2013]

USDA Forest Service (2010) FY 2010 aviation safety summary. National Aviation Safety Center. (Boise, ID) Available at http://www.fs.fed.us/fire/av_safety/assurance/fy_safety_reports/fy2010_summary.pdf [Verified 22 January 2013]

USDA Forest Service (2011*a*) National exclusive use airtanker service contract, Section C-1A. Available at www.fs.fed.us/fire/contracting/airtankers/airtanker_contract.pdf [Verified 22 January 2013]

USDA Forest Service (2011*b*) US Forest Service cancels airtanker contract with Aero Union. News Release number 1127. Available at http://www.fs.fed.us/news/2011/releases/07/airtanker.shtml [Verified 22 January 2013]

USDA Forest Service (2012). Large airtanker modernization strategy. Available at http://www.fs.fed.us/fire/aviation/airtanker_modernization_strategy.pdf [Verified 22 January 2013]

USDI, USDA (2004*a*) Communication plan: termination of large airtanker contract. Available at http://wildfirelessons.net/documents/airtankers_comm_plan_051004.pdf [Verified January 2013]

USDI, USDA (2004*b*) Federal firefighting agencies will return two additional large airtankers to service, will monitor plane stress in fire environment. News Release number 0333.04. Available at http://www.usda.gov/wps/portal/usda/usdahome?contentid=2004/08/0333.xml&navid=NEWS_RELEASE&navtype=RT&parentnav=LATEST_RELEASES&edeployment_action=retrievecontent [Verified 22 January 2013]

USDI, USDA (2005) Transcript of tele-news conference with Under Secretary for Natural Resources and the Environment, Mark Rey. USDA Release number 0191.05. Available at http://www.fs.fed.us/news/2005/releases/05/air-tanker-transcript.pdf [Verified 22 January 2013]

USDI, USDA (2010) Wildland firefighter safety, calendar year 2010 report. Report to Congress.

Venn TJ, Calkin DE (2011) Accommodating non-market values in evaluation of wildfire management in the United States: challenges and opportunities. *International Journal of Wildland Fire* **20**(3), 327–339. doi:10.1071/WF09095

Western Forestry Leadership Coalition (2009) The true cost of wildfire in the western US. Available at http://www.blm.gov/or/districts/roseburg/plans/collab_forestry/files/TrueCostOfWilfire.pdf [Verified 22 January 2013]

Wibbenmeyer MJ, Hand MS, Calkin DE, Venn TJ, Thompson MP (2013) Risk preferences in strategic wildfire decision making: a choice experiment with US wildfire managers. *Risk Analysis* **33**(6), 1021–1037. doi:10.1111/J.1539-6924.2012.01894.X