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Airtankers and wildfire management in the US Forest Service: examining data availability and exploring usage and cost trends

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Abstract. Evaluating the effectiveness and efficiency of fixed- and rotary-wing aircraft is a crucial component of strategic wildfire management and planning. In this manuscript, we focus on the economics of fire and aviation management within the US Forest Service. Substantial uncertainties challenge comprehensive analysis of airtanker use, prompting calls from federal oversight agencies for improved aerial firefighting data collection and analysis. Here, we explore the availability and sufficiency of agency aviation data to track airtanker use and cost trends, and to categorise airtanker use by mission type and fire size class. Although the primary intended use of the airtanker fleet is for initial attack of wildfires, our results indicate that the use of these aircraft tends to occur for extended attack or large- fire support, with a significant number of flights associated with very large fires greater than 4047 ha (10 000 acres). Our results highlight apparent trends in airtanker use that challenge our ability to evaluate cost-effectiveness of airtankers. Data quality and availability issues limited our analysis, leading to a recommendation for improved data collection on flight objective and drop location. We conclude by offering suggested avenues of future research that may help address informational and analytical shortcomings.

Additional keywords: aviation, cost–benefit analysis, suppression.

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Introduction

Evaluating the effectiveness and efficiency of fixed- and rotary-wing aircraft is a crucial component of strategic wildfire management and planning. In this manuscript, we focus on the economics of fire and aviation management within the US Forest Service, which currently contracts an aging fleet of fixed-wing airtankers for wildfire management but is exploring fleet modernisation opportunities. As of 2010, the airtanker fleet comprised 19 surplus military aircraft, with model year ranging from 1954 to 1964, and retardant load capacity ranging from 7881 L (2082 gallons) to 9653 L (2550 gallons). The Forest Service recently released an airtanker modernisation strategy, which calls for updating the fleet with a mixture of Type 1 (>11 356 L) and Type 2 (6813–11 353 L) airtankers (USDA Forest Service 2012). A fundamental tenet of the replacement strategy, and of existing guidance for aerial firefighting, is that airtanker use must be cost-effective (National Wildfire Coordinating Group 2011). Challenging economic analysis of airtanker use is substantial uncertainty regarding aerial firefighting effectiveness, especially for large fires (Finney *et al.* 2009; USDA Office of Inspector General 2009).

Thus improved aerial firefighting data collection and analysis are warranted. This conclusion is shared by the US General

Accounting Office (US General Accounting Office 2007), which recommended the Forest Service develop improved systems for ‘recording and analysing data about the cost and use of these assets at the time of the fire’. Further motivating analysis of airtanker use are questions from federal oversight agency investigations, economic analyses and investigative reports regarding the efficiency of historic airtanker use (Donovan and Brown 2005; US General Accounting Office 2007; Cart and Boxall 2008; Donovan *et al.* 2008). The possible inefficient use of aviation resources is of great concern owing to escalating suppression expenditures and limited success to date in achieving cost-containment objectives (US General Accounting Office 2009; USDA Office of Inspector General 2009). An enhanced ability to characterise airtanker usage could highlight opportunities for increased efficiency and inform estimates of fleet effectiveness.

A prerequisite for deriving estimates of airtanker effectiveness is the ability to track the location of airtanker drops and evaluate alignment of outcomes with specific mission objectives, given information on the fire environment (weather, terrain, etc.). To date, this information has not been available, limiting opportunities to characterise effectiveness. Here, we begin by exploring the availability and sufficiency of extant

agency aviation data to answer these questions, and to the extent possible, to quantify trends in airtanker use, cost and mission type. Our work is not intended to be a comprehensive analysis of federal fire-aviation management, but rather to highlight information deficiencies and to identify key research needs, in particular as they relate to the prominent, policy-relevant question of potential airtanker acquisition.

The remainder of this manuscript is organised as follows: first, we briefly review aerial firefighting and past studies that have attempted to model effectiveness. Second, we provide context for aerial firefighting and optimal fleet design in the United States. Third, we describe our analytical methods, which entailed the design, creation and querying of a database assembled from US Forest Service aviation, finance and fire incident records in order to categorise and understand large-airtanker use. After presenting results, we discuss implications of our findings, and last, we conclude with recommended avenues of further research.

Aerial firefighting and modelling studies

Wildfire-management aircraft perform a multitude of duties, including reconnaissance, personnel and equipment transport, and, most relevant to this discussion, firefighting. Aviation firefighting resources can create containment lines (hereafter, fireline(s)) before arrival of ground resources, can augment the fireline-producing capacity of ground-based firefighting resources and can further provide point protection for structures and other threatened assets. Types of aircraft include helicopters, single engine airtankers (SEATs), fixed-wing water-scooping aircraft (scoopers) and multi-engine large airtankers. These aerial resources differ in terms of costs, flight speed, coverage distance, turnaround time, manoeuvrability, tank capacity and the type and effectiveness of material (water, suppressant or retardant) able to be delivered.

Use of firefighting aircraft varies throughout the world, a function of accumulated experience, management legacy, resource availability, environmental factors, fire regimes and associated fire-management needs. In Australia, for instance, helicopters and SEATs are common whereas scoopers and multi-engine airtankers are thought to be less effective (Plucinski 2010; Plucinski *et al.* 2007). In the Mediterranean countries of Europe, the close proximity of the sea to the most flammable forest lands makes the use of scoopers quite prevalent and helicopters are also widely used. In the United States, by contrast, multi-engine airtankers play a predominant role in federal wildfire management, along with SEATs, helicopters and limited use of very large airtankers and scoopers. Key advantages of airtankers include their ability to quickly travel long distances to reach remote fires and their relatively large storage capacity, which enables bursts of high fireline productivity provided by retardant drops. For the purposes of this paper, we limit our analysis to fixed-wing airtankers.

Relative to ground-based resources, the main advantage of aircraft use for wildfire suppression is their ability to quickly

reach the fire and prevent spread before the fire grows large (USDA Forest Service and DOI 1995; USDA Forest Service and DOI Bureau of Land Management 1996; McCarthy 2003; Fire Program Solutions 2005; Plucinski *et al.* 2007; Ganewatta and Handmer 2009). As such, aircraft use in wildfire management is often prioritised for initial attack operations, which are typically defined by size limits or time windows within which the fire should be contained. In the United States, the primary intended use of the airtanker fleet is for initial attack^A of wildfires (Rey and Scarlett 2004; USDA Forest Service 2011). It is important to note that definitions of initial attack, extended attack and large-fire support differ by purpose. For reporting purposes, fires greater than 121 ha (300 acres) are generally considered large wildland fires, and firefighting operations associated with them are described as in extended attack or large-fire support rather than initial-attack mode. Operationally, however, fires can be much larger while still seeing initial-attack activities in the first burn period and the National Wildfire Coordinating Group glossary (see <http://www.nwccg.gov/pms/pubs/glossary/index.htm>, accessed 1 November 2011) does not mention fire size when defining extended attack.

Attempts at characterising the effect of aerial firefighting typically model aircraft as creating containment lines with successive drops and analyse outcomes by comparing the rate of fireline production with the rate of perimeter growth of the fire (Mees *et al.* 1994; Fried *et al.* 2006; Podur and Martell 2007; Alexandridis *et al.* 2011). Aircraft differ from ground-based firefighting resources in response time, cycle time and fireline production rate. In this modelling context, where the cumulative fireline building capacity of ground and aerial firefighting resources exceeds the growth rate of the fire, the fire is successfully contained. In practice, airtanker productivity varies with environmental characteristics such as wind speed and direction, flight and drop pattern, topography and fuel type, among other factors. Empirical investigations of effectiveness (George 1985) in operational firefighting environments across a diversity of conditions to inform modelling efforts are quite limited, although recent research using remote sensing techniques offers promise (Pérez *et al.* 2011), as does formalised incorporation of expert judgment (Plucinski *et al.* 2011).

Information to support modelling efforts is particularly limited for extended attack and for large-fire support operations. Most investigations into the efficiency of aerial firefighting have focussed exclusively on initial attack (Greulich and O'Regan 1975; Hodgson and Newstead 1978; Greulich and O'Regan 1982; MacLellan and Martell 1996; Islam and Martell 1998; Fried *et al.* 2006). The literature contains very few applications of operations research to large-fire management problems (Martell 2007), which are limited by overly simplistic models of fire (Hof *et al.* 2000), the acknowledgement that little is known regarding aerial drop effectiveness (Mees and Strauss 1992; Mees *et al.* 1994; Podur and Martell 2007), or a lack of ability to distinguish productivity across suppression resources (Wei *et al.* 2011). Airtanker use for extended attack and large-fire support is more complex than initial attack, requiring not

^AThe Forest Service FY 2011 Guidance for Use of Incident Job Codes (http://www.fs.fed.us/fire/ibp/cost_accounting/2011_incident_job_code_direction.pdf, verified 2 July 2012) transitions to a lexicon using 'initial response' and 'extended response'. Here, we largely retain the phrases 'initial attack' and 'extended attack', which we consider more consistent with international use and past use within the US.

only consideration of line-building capabilities but also the effectiveness of retardant delivery for point protection and the benefits of buying time by delaying rather than preventing eventual fire spread. In summary, 'the effectiveness of suppression efforts on the progress or containment of large fires has not been modeled or even characterised, and it is presently not known what or how different factors are related to successful containment' (Finney *et al.* 2009). Thus, we have a limited body of knowledge with which to analyse initial attack operations, and insufficient knowledge and data to credibly model outcomes with and without airtanker use for extended attack and large-fire support.

Forest Service management of large airtankers in the United States

The Forest Service is faced with important questions of how to utilise existing, aging aircraft and how to safely and cost-effectively manage future aviation firefighting. A report on aerial firefighting safety and effectiveness commissioned in response to fatal accidents in the 2002 fire season identified a series of key problems, including that the safety record of fixed-wing aircraft and helicopters was unacceptable and that organisational, structural and managerial factors could compromise the safety and effectiveness of wildland fire management (Blue Ribbon Panel 2002). In fiscal year^B 2004, the airtanker fleet was reduced when the contracts with 33 airtankers comprising the national Forest Service and Bureau of Land Management fleet were terminated 'due to concerns over their airworthiness' (Rey and Scarlett 2004).

Earlier nationwide studies within the United States (USDA Forest Service and DOI 1995; USDA Forest Service and DOI Bureau of Land Management 1996) identified 38 airtankers as an optimal federal fleet size, based exclusively on meeting initial attack demand. The studies further noted 'extensive use' of aircraft on fires larger than 40 ha (100 acres), and argued for an additional three airtankers for large-fire support (bringing the total recommended fleet size to 41 airtankers). A 2005 follow-up study (Fire Program Solutions 2005) confirmed the results of these earlier studies, stating that airtankers are an 'integral component' for initial attack.

Issues of data adequacy led the Forest Service to exclude these results in a recent submission to the Office of Management and Budget (USDA Office of Inspector General 2009). An important limitation of these studies is that no attempt was made to model airtanker use on changing large-fire outcomes. Rather, observed historic use on large fires was implicitly assumed to be efficient without examination of costs or contribution to suppression operations.

To briefly summarise, airtanker use in the United States is subject to uncertain trade-offs regarding safety and cost relative to perceived effectiveness, and previous modelling efforts attempting to derive optimal fleet compositions have explicitly assumed near-exclusive use for initial attack. Assumptions regarding airtanker use and effectiveness have not to date been empirically demonstrated. Insufficient data thus make

performing a comprehensive cost-effectiveness analysis of large airtanker use extremely challenging, if not altogether infeasible (USDA Office of Inspector General 2009). Understanding how the current fleet is used is a necessary component to project how increases or decreases in the current fleet size might change wildfire outcomes.

Methods

We queried US Forest Service aviation, finance and fire-incident records in order to categorise and understand large airtanker use. In total, we obtained records for 20 765 flights. Our analysis required integrating information from multiple platforms, and in some cases further required development of heuristic logic to deal with missing or incorrect data and a lack of metadata. We focussed on two major themes: (1) airtanker usage and cost statistics (number of flights, flight time, etc.) and how these may have changed in the wake of the fleet reduction and, more importantly, (2) airtanker mission type, in terms of initial attack, extended attack and large-fire support. Owing to data sufficiency and availability issues, we were only able to analyse airtanker mission type for fiscal years 2007–10.

Analysing airtanker use and cost trends

We acquired airtanker empirical data from the US Forest Service's Aviation Business System (ABS) database. ABS became functional in 2007. It replaced and inherited records from the Aviation Management Information System (AMIS), via phased implementation, as the system of record for Forest Service aircraft usage data. We drew large-airtanker flight time records on 28 October 2010 from the ABS Queries and Reports page of the FAMWEB Data Warehouse (see http://famtest.nwcg.gov/fam-web/help/famweb_data_warehouse/fdw_topic_areas/fdw_aviation_management.htm, accessed 24 February 2012) for the entire United States for fiscal years 1993–2010. With these data, we then designed a database so we could analyse use and cost trends over time. The fundamental unit of analysis is a flight, which is recorded every time an aircraft takes off after reloading. A load can be split into multiple drops depending on mission objectives. Detailed descriptions of tables and queries within the airtanker use database are available from the authors on request.

Analysing airtanker mission type

To characterise airtanker mission type requires information regarding fire size and other characteristics of the incidents to which aircraft were deployed, and ultimately requires clear articulation of flight and overall incident objectives. Unfortunately, the ABS database does not directly provide this information. We adopted two approaches to characterise airtanker mission type by proxy, first by incident job code use description (Table 1), and second where feasible by matching flight records to fire perimeter information collected from the Geospatial Multiple-Agency Coordination (GeoMAC) Group (see <http://www.geomac.gov/>, accessed 1 November 2011). Fig. 1 provides a conceptual model of our relational database for

^BIn the United States, a fiscal year extends from 1 October through 30 September. The fiscal year largely overlaps with typical fire seasons for most regions of the country.

Table 1. Airtanker job code use categories
Forest Service fiscal year 2011 job code descriptions use 'response' rather than 'attack'

Use	Description
Forest Service Extended response	Extended response (>121 ha (300 acres)) and fires less than 121 ha (300 acres) that have one of the following criteria: human-caused, trespass, expected reimbursement, cost share, or a Type 1, 2 or 3 incident-management team assigned
Forest Service Initial response	Initial response fires (<121 ha (300 acres)), false alarm codes and extended response fires if less than 121 ha (300 acres)
FEMA Incident support	Federal Emergency Management Agency support
BIA Support	Bureau of Indian Affairs assistance
BLM Support	Bureau of Land Management assistance
NPS Support	National Park Service assistance
FWS Support	Fish and Wildlife Service assistance
Non-wildland Federal Fire Departments	Included but not limited to the Department of Defence and the Tennessee Valley Authority
Non-Federal support	Forest Service support of non-federal fires
Severity assistance	Assistance to the Department of the Interior severity authorisations
Staging	Flights coded for prepositioning
Administratively Determined Support	Training and work capacity testing
Resource benefit	Lightning-caused fires that are managed for resource benefits

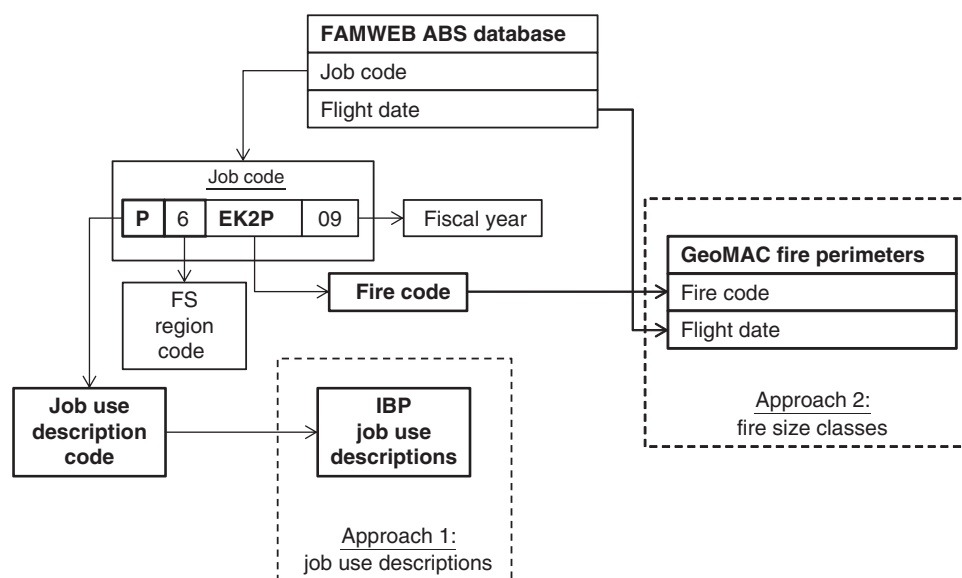


Fig. 1. Relational database model for analysing airtanker mission type. For all flights, we first analysed job use code descriptions to characterise mission type (Approach 1). Further, for fires for which we could match flight records (fire code and flight date) to GeoMAC fire perimeters (at the date of the drop), we analysed flights by fire size (Approach 2).

analysing airtanker missions, which relates three key pieces of information: the fire code, the incident job code and the flight date.^C

The incident job code is an eight-digit alphanumeric string that links information about the flight mission and the fire incident. As an example, with 'P6EK2P09' the first character (P) is the job use code, the second character (6) is the Forest Service region number in which the fire is located, the third, fourth, fifth and sixth characters (EK2P) are a unique identifier from the fire code system, and the last two digits (09) correspond

to the fiscal year. Job codes are assigned to every fire incident following guidance from the Incident Business Practices (IBP) website, which coordinates business practices for wildfire, non-fire and Federal Emergency Management Agency emergency responses for the US Forest Service (see <http://www.fs.fed.us/fire/ibp/archives/archives.html>, accessed 1 November 2011). We compiled job-code look-up tables using IBP job-code spreadsheets and related these back to job-use descriptions.

With the job-use descriptions, we aimed to ultimately classify flights according to whether they were for initial-attack

^CAMIS data did not include some of this information, so relating older flight information to incidents was difficult and could be incomplete.

operations. Ideally, the job-use codes would classify flights into two fire size classes accurately for every agency: fires greater than and less than 121 ha (300 acres). Because the guidelines for initial- and extended-attack classes overlap when fire sizes are less than 121 ha, it's not clear what proportion of initial-attack-coded fires is in extended attack, and not clear what proportion of extended-attack-coded fires are less than 121 ha.

Because job code use descriptions do not clearly differentiate fire size classes, we used fire perimeter data to ascertain fire size. We matched flight records to fire perimeter size classes using data collected from the GeoMAC group website for calendar years 2007–10. GeoMAC is an internet-based mapping tool originally designed for fire managers to access online maps of current fire locations and perimeters in the conterminous 48 states and Alaska. Perimeters are located by or submitted to GeoMAC from various sources and local field offices. These data are then compiled and posted to an outgoing database website through the Rocky Mountain Geographic Science Center for downloading (http://rmgsc.cr.usgs.gov/outgoing/geomac/historic_fire_data/, verified 2 July 2012). Archive files contain all fire perimeters that were located by or submitted to GeoMAC for a given year. Current archived datasets have perimeters dating back to the year 2000. We matched airtanker flights to fire perimeters by extracting the four-digit alphanumeric fire code embedded within the job code and linking to the fire code within the GeoMAC fire perimeters look-up table.

The GeoMAC website is not an all-inclusive archive for all fire incident data; 7546 flights could not be matched to a GeoMAC fire perimeter. Fire perimeter compilation quality varies throughout the GeoMAC dataset for those fires we could match ($n = 13\,219$). Generally, fire perimeters are digitised into a spatial format approximately once per day over the duration of the fire incident. From these data, we can extract an estimated fire size from each daily perimeter. Using the fire code, we can match an airtanker flight to an approximate fire perimeter size on the day of the flight using a simple parsing logic as described below.

For an airtanker flight where the fire code matches a fire perimeter code:

- if the flight date = perimeter date: assign the flight the minimum recorded fire perimeter fire size ($n = 7030$)
- if the flight date > latest perimeter date: assign the flight the maximum recorded fire perimeter size ($n = 1812$)
- if the flight date < latest perimeter date: assign the flight the minimum recorded fire perimeter size ($n = 4377$).

It is expected that this parsing scheme will reasonably capture flight use by fire size, but errors are possible, particularly regarding fire complexes. Fire complexes are areas that have concurrent fires indicated by multiple polygons recorded for any given day within the GeoMAC perimeter dataset. Our parsing logic assumes that airtankers are primarily used for initial attack and will assign a flight the minimum recorded size for all fires including fire complexes except when the flight date is greater than the latest perimeter date. In this case, the maximum recorded fire perimeter size is assigned to the flight. As an example, assume that a fire complex has three separate polygons (x , y and z) with the following areas: $x = 100$ ha, $y = 250$ ha,

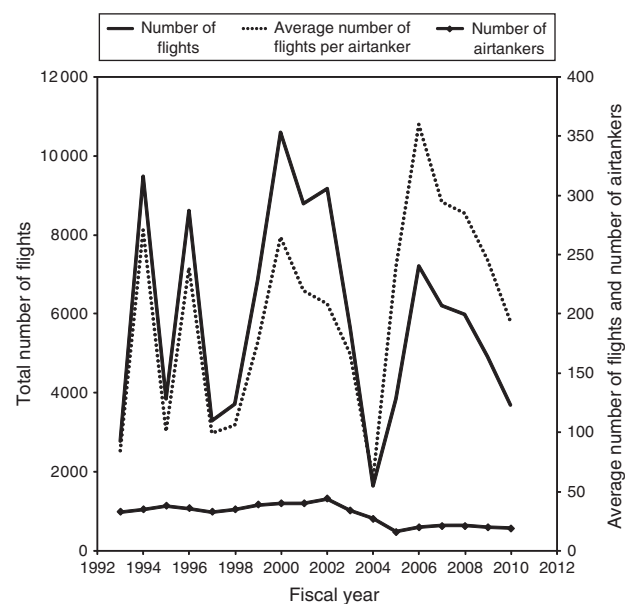


Fig. 2. Summary findings for airtanker fleet size and utilisation trends across fiscal years 1993–2010. Airtankers are contracted by calendar year, though we report fleet size by fiscal year to be consistent with other quantities reported from Aviation Business System (ABS).

recorded on 9 July, and $z = 1000$ ha recorded on 12 July. Assume a flight flew to this fire complex on 9 July. Using the parsing logic, the flight will be assigned fire size x because the flight date equals the perimeter date of 9 July, and the minimum perimeter size of 100 ha is assigned. If a flight occurred on 11 July, the flight is assigned fire perimeter y because the flight date is greater than the perimeter date of 9 July and the maximum recorded area is assigned from all perimeters recorded before the flight date. Finally, if a flight occurred on 15 July, the flight is assigned fire perimeter z because the flight date is greater than the latest perimeter date.

For summary purposes, we categorised flights with perimeter matches into 13 fire size classes. Traditionally, fire size classes are broken into seven separate classes (A–G) each representing a range of fire sizes (see <http://www.nwcg.gov/pms/pubs/glossary/index.htm>). As size class G represents all fires greater than 2023 ha (5000 acres), our ability to analyse airtanker use on very large fires that typically accrue the greatest suppression costs would be limited. We therefore added six additional fire size classes H–M. In our classification scheme, we redefined fire size class G as 2023–4047 ha (5000–10 000 acres), and established H as 4047–8094 ha (10 000–20 000 acres) and I–L in 8094-ha (20 000 acre) increments up to size class M, with size class M representing fires greater than 40 469 ha (100 000 acres) in size.

Results

Airtanker use and cost trends

Fig. 2 summarises findings on airtanker flights logged (solid line – left y-axis), average flights per airtanker (dashed line – right y-axis) and fleet size (marked lines – right y-axis) for fiscal

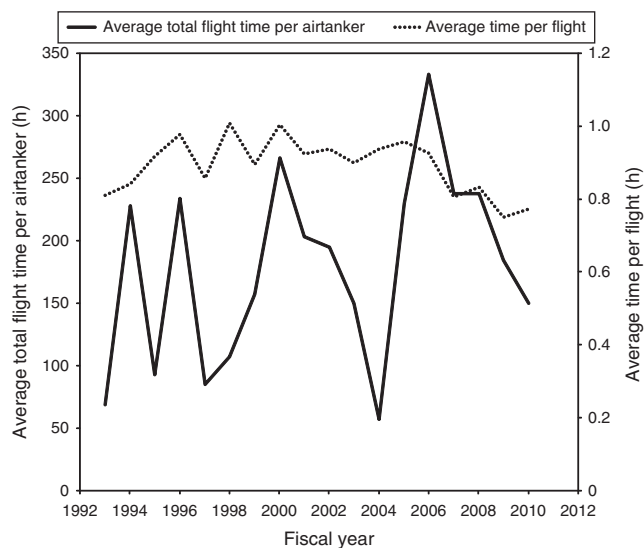


Fig. 3. Summary findings for airtanker total flight time per airtanker and average time per flight trends across fiscal years 1993–2010.

years 1993–2010. The number of airtankers reported in the ABS database as contracted to the Forest Service and flying within any region ranged from a high of 44 in fiscal year 2002 to a low of 16 in fiscal year 2005. In fiscal year 2004, the airtanker fleet reduction began, and by 2005, the airtanker fleet was 36% of its peak size. The high inter-annual variability in airtanker use reflects fire season variability, although some trends are evident. The number of flights per year expectedly experienced a sharp drop in 2004 and in subsequent years, there are generally fewer flights logged per year (1993–2003 average = 6606 flights; 2005–2010 average = 5299 flights). However, the average number of flights per aircraft per year increases dramatically after 2004, peaking at 359.75 in 2006 and averaging 269.74 flights per airtanker per year for fiscal years 2005–10 (relative to 175.75 for fiscal years 1993–2003).

Fig. 3 presents results on average total flight time per airtanker (solid line – left y-axis) and average time per flight (dashed line – right y-axis) for fiscal years 1993–2010. The average total flight time per airtanker follows a pattern similar to average flights per airtanker (Fig. 2, dashed line), peaking in 2006 at 332.95 h per airtanker and averaging 228.51 flight hours per airtanker per year for fiscal years 2005–10 (relative to 162.14 for fiscal years 1993–2003). Average time per flight appears to trend downward beyond fiscal year 2005. Although reduced flight time can be used as an indicator of gains in ferrying or prepositioning efficiency, examining possible causes for this downward trend is beyond the scope of this paper.

Fig. 4 presents information on overall airtanker costs (solid line, left y-axis), which include both flight time and availability cost and average flight cost (dashed line – right y-axis). All cost estimates are summarised by fiscal year in 2010 US dollars, adjusted for inflation using the consumer price index. Total cost and average flight cost have continued to increase even as the fleet size decreased. Increases in cost may be attributable to increasing fuel prices, as well as the reduction in fleet size and subsequent increase in flight times for prepositioning.

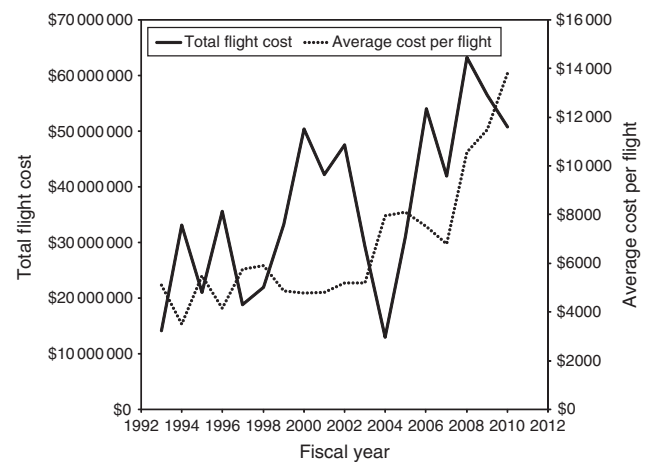


Fig. 4. Summary findings for airtanker total flight cost (including flight and availability time) and average cost per flight trends across fiscal years 1993–2010.

Airtanker mission type results

Fig. 5 presents recorded job-code descriptions for all flights, averaged across fiscal years 2007–10 (Approach 1). Only 6.6% of flights were explicitly labelled initial attack. By contrast, extended attack comprised 49.7% of all flights, with non-federal support the second highest recorded use at 22.7%. It is possible that many of the flights recorded for federal and non-federal support were for initial-attack operations. If we grouped all job codes not labelled extended attack into initial attack (exclusive of staging and administratively defined support), it would raise the overall share of initial attack from 6.6 to 48.1% of the recorded flights.

Fig. 6 presents airtanker flights summarised by size class using fire codes as a method to match airtanker flights to GeoMAC fire perimeters (Approach 2). These results suggest that the dominant use of airtankers is for extended attack and large-fire support. Averaged across the years 2007–10, initial-attack fires (size classes A–D) comprise only 10.8% of total flights linked to a fire perimeter. The most flights (25.4%) are associated with fire perimeter class F (405–2023 ha; 1000–5000 acres), followed by 15.21% for G (2023–4047 ha; 5000–10 000 acres) and 13.8% for E (121–405 ha; 300–1000 acres). To estimate an upper bound for initial attack with Approach 2, we grouped all flights matched to fire size classes A–D ($n = 1429$) and assumed all flights without a perimeter match ($n = 7546$) were for initial attack. By that measurement, an upper bound for initial-attack flights is 43.2%.

Fig. 7 similarly presents flights distributed according to fire size, but displays results by the cumulative percentage of all flights by fire size category. This graph confirms the result that the majority of airtanker use is for extended attack, and in particular that a significant proportion of airtanker use is for large-fire support and well beyond initial-attack efforts. Flights associated with fires 8094 ha (20 000 acres) and larger (I–M) comprise 22.8% of all flights; those associated with fires 4047 ha (10 000 acres) and larger (H–M) comprise 34.7% of all flights, and those associated with fires 2023 ha (5000 acres) and larger (G–M) comprise 49.9% of all flights.

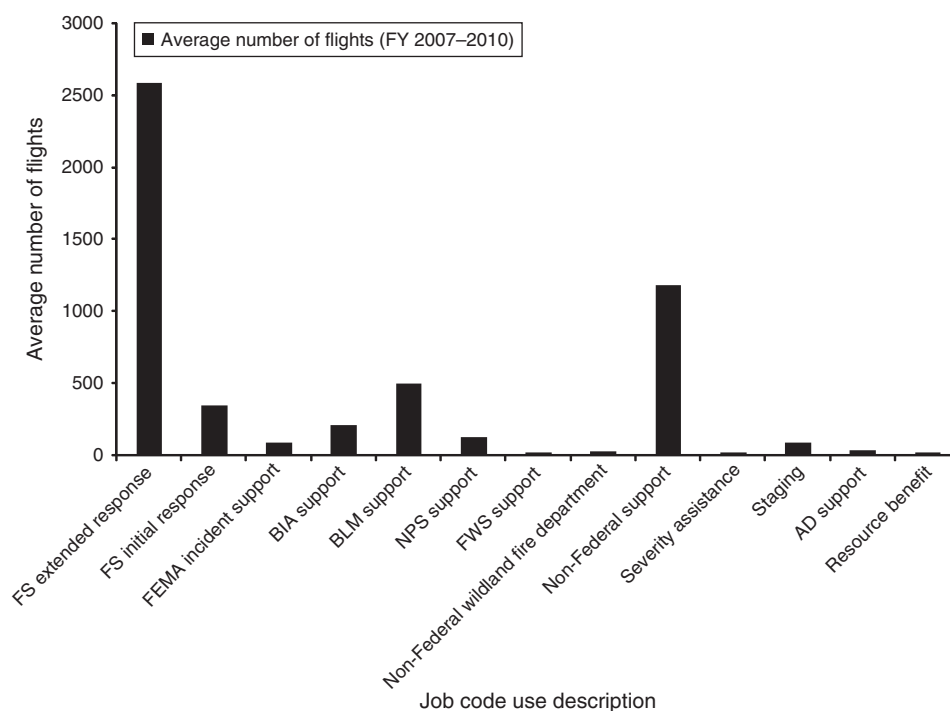


Fig. 5. Job code use descriptions for all airtanker flights averaged across fiscal years 2007–10 (x-axis labels relate to job codes presented in Table 1).

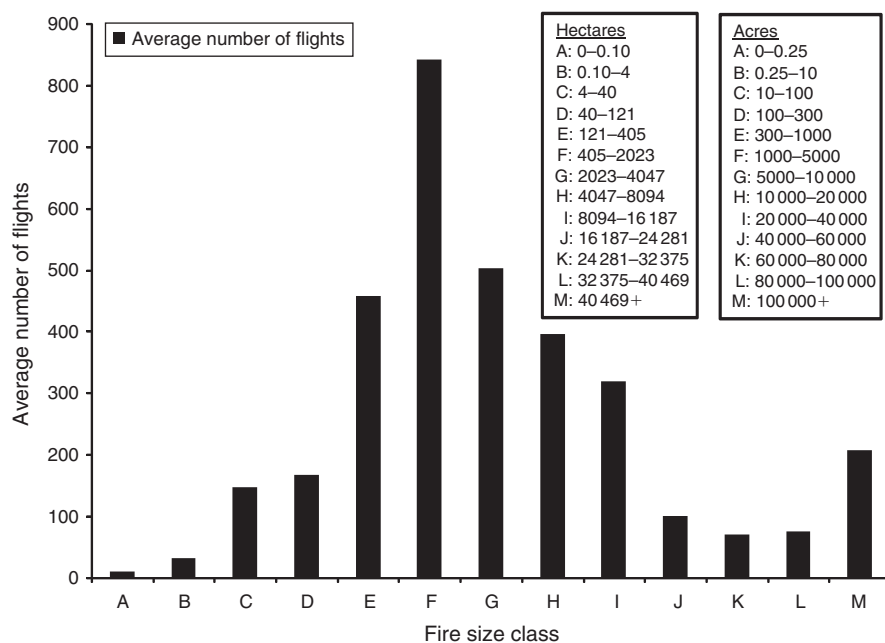


Fig. 6. Airtanker flights by size class within the United States for fiscal years 2007–10, for fires with perimeter matches ($n = 13\,219$). Units are reported in acres, consistent with established USA federal fire size classes for reporting purposes.

In summary, data quality and reporting standards make difficult an accurate assessment of airtanker mission type, although both approaches we adopted suggest significant use for extended attack and large-fire support. Lower bounds

derived with both approaches put airtanker use for initial-attack operations in the range of 6.6–10.8% of all flights. Upper bounds put airtanker use for initial attack in the range of 43.2–48.1%.

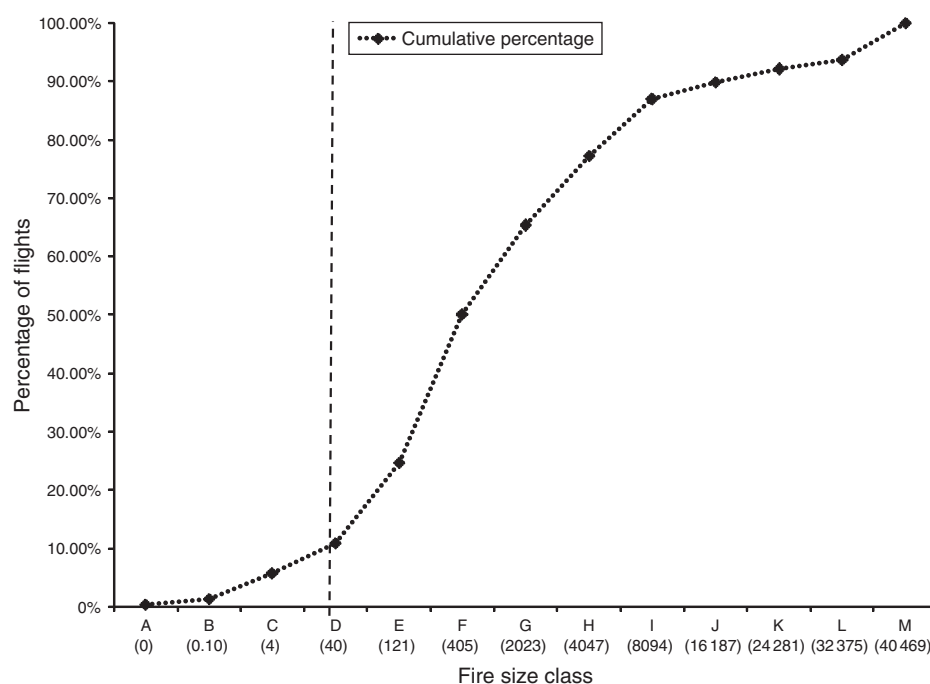


Fig. 7. Cumulative percentage of all flights matched to fire perimeter ($n = 13\,219$), sorted in order from smallest to largest fire size class, with minimum fire sizes (hectares) presented in parentheses. The dashed vertical line demarcates IA fires (size class A–D).

Discussion

Initial attack is thought to be the operational firefighting phase in which airtankers are most effective, and agency policy prioritises airtanker use for initial attack. Our work, however, indicates that extended attack and large-fire support currently comprise the majority of airtanker use, reflecting an apparent disconnect between intentions and actual practice. These results highlight apparent trends in airtanker use that challenge justification on a cost-effectiveness basis. In particular, our results spotlight and may call into question the use of airtankers on very large fires that are known in many circumstances to be driven primarily by weather and are largely immune to suppression efforts (Finney *et al.* 2009), and which comprise a large share of suppression costs. Our results analysing airtanker use and costs collectively indicate high utilisation rates of the fleet across mission type, increasing costs and increasing number of flights per airtanker, which could accelerate wear and tear. Issues related to firefighter safety and higher fatality rates of aerial firefighting must also be considered (Blue Ribbon Panel 2002; McKinney 2004; Wildland Fire Lessons Learned Center 2007) in the context of calls for additional use of airtankers.

However, that apparent use of airtankers does not align with what is thought to be their most efficient use does not necessarily suggest large-scale inefficiencies. Airtanker use outside initial attack is acceptable insofar as the use is essential to completion of the incident objectives and insofar as the use isn't diverting resources from initial-attack needs – large airtankers tend to fly more missions when used during large-fire support and thus may be unavailable for initial attack (Blue Ribbon Panel 2002). Extended attack and large-fire support could be largely

opportunistic, capitalising on any airtanker surplus after initial-attack demands have been met. Given a fleet designed to meet peak demand from pulses of fire starts, one would expect a surplus of airtankers on days of average or fewer-than-average ignitions. Even so, use of surplus airtankers outside initial attack is subject to economic efficiency requirements.

There are some mitigating factors to consider when interpreting our results. First, the boundary between initial attack and extended attack (121 ha; 300 acres) is arbitrary, and although useful for reporting purposes does not reflect other management considerations such as burning periods or operational attack periods. We might expect a moderate amount of airtanker use on size class E (121–405 ha; 300–1000 acres) or even size class F (405–2023 ha; 1000–5000 acres) fires, owing to incident objectives, and timing issues associated with fire detection, mobilising resources and flying to the drop location, especially for remote fires. Fires that are more complex and difficult to manage are perhaps more likely to receive calls asking for airtanker assistance. Hence, we might expect a larger proportion of fires receiving airtanker support to escape initial-attack efforts, in turn leading to airtanker support for extended attack.

A larger concern relates to the availability and quality of data we analysed. The ABS database was designed primarily as a financial accounting and tracking tool, not for our purposes (this is also the case with the older AMIS database). Detailed ABS database documentation is difficult to obtain. Of the information ABS does record (flight time, date and origin of a flight, aircraft type and owner, retardant volumes dropped, job code and cost information), many fields are not mandatory, so there are holes throughout the dataset. For instance, we found that ~24% of all

flight records provided either zero or a null value for retardant volumes dropped. Other reporting systems track retardant dropped by tanker base, but do not match retardant quantities to agencies, specific aircraft or incidents.

Associating fire-incident information with flight data requires linking together databases from multiple sources with different database architectures, all of which have errors. Our analyses suggest airtanker use for initial attack comprises somewhere between 6.6 and 48.1% of overall flight use, which is far too non-specific and primarily reflects a need for improved data collection and management by the Forest Service and other federal agencies with wildfire-management responsibilities. At present, there are too few years of observations, and too many uncertainties in the data we do have, to make strong inferences regarding airtanker use and effectiveness relative to a suite of important variables (fire season severity, fleet size, etc.). With improved geospatial data on drop locations and fire perimeters, we could better understand airtanker use by mission and better match drop quantity and location to fire outcomes.

More important than identification of mission type by proxy through job-use description or fire size is the identification of specific mission objectives. Flight missions should have well-articulated objectives and should clearly align with overall incident objectives. Without such information, our ability to analyse fire outcomes and airtanker effectiveness will be severely limited. For instance, retardant drops for point protection would be evaluated quite differently than drops in support of ground resources building fireline. Mission objectives are likely to overlap across initial attack, extended attack and large-fire support, further highlighting the need to evaluate flights by mission objective not just mission type.

Ultimately, there is a need for improved data management and expanded research to better analyse airtanker use and effectiveness, and more broadly, aerial and ground-based firefighting resources. Identifying drop locations and mission objectives are critical for effectiveness research. Two additional key recommendations are to expand the scope and purpose of the ABS database to include comprehensive monitoring, performance evaluation and research purposes, and to increase the reporting rate to and accuracy of flight data in ABS. We found matching flights to GeoMAC fire perimeters by date and categorising by fire size class (Approach 2) provided a more complete picture of airtanker use across fires. Creation and maintenance of geospatial daily fire perimeters for a more complete set of wildfires would enable improved characterisation of airtanker use and effectiveness, cross-referenced with flight mission objectives and especially retardant drop location.

A fundamental research need is an ability to determine drop effectiveness as a function of mission objective, the fire environment (fuels, weather, and topography), fire behaviour, flight and drop pattern, delivery system and engagement of retardant drops with fire. Drop test data show that airtanker deposition patterns are highly sensitive to many factors, including release altitude, prevailing winds and flow rate from the tank, all of which usually vary significantly from tested conditions during normal operations (R. Becker, Forest Service San Dimas Technology Development Center, pers. comm.). Analysis of deposition patterns in more representative firefighting conditions

would enable correlation of actual tactical airtanker use with performance on a specific fire. By evaluating the effectiveness of drops under variable conditions, guidance can eventually be provided to focus on those situations where usage is most beneficial. Additional analysis could then align information on conditions under which flights can be cost-effective with information on conditions where safety risks associated with firefighting are acceptable.

Improved data on fleet use and effectiveness in turn inform simulation modelling capabilities, crucial for evaluating consequences of alternative fleet management or acquisition strategies. Expanding the scope and improving the logic of modelling capabilities are also recommended, for instance an improved ability to model the behaviour of aerially delivered firefighting liquids (Amorim 2011a, 2011b), and to jointly model fireline production of other firefighting resources. Simulation of firefighting could include a more comprehensive range of operational use, including direct attack, indirect attack and localised resource protection (Fried *et al.* 2006).

Conclusions

Uncertainty regarding airtanker effectiveness, especially for extended-attack and large-fire support operations, challenges attempts to perform comprehensive cost-effectiveness analyses. Most investigations have focussed exclusively on initial attack, for which modelling methods are more mature, retardant drops are assumed more effective at restricting fire growth, where most large airtanker use is assumed to occur, and, perhaps most importantly, where policy guidance recommends airtanker use. Through a compilation of large airtanker aviation usage data from multiple databases, we present results suggesting that, with respect to US Forest Service fire-management operations, large airtanker use occurs more often in extended attack and large-fire support than for initial-attack suppression. Our results also demonstrated increased per-tanker usage rates in recent years since the fleet reduction. Not only is this causing additional wear and tear on existing aircraft and possibly hastening the need for replacements, but it also raises questions of air-worthiness and concerns over pilot safety. In the same time-frame, annual airtanker-related expenditures have increased dramatically despite reductions in total flights per year.

Federal oversight agencies have recommended that the Forest Service needs clearly defined aviation performance measures that can directly demonstrate a cost-effectiveness from firefighting aircraft, and needs to collect performance data to demonstrate the effect of aircraft on firefighting performance. Our aim with this research effort is to better monitor airtanker use and cost trends in order to meet oversight agency recommendations such as these. In the course of our work, we uncovered a suite of issues relating to data availability, quality and consistency across databases. We identified informational needs to better monitor and characterise airtanker use in the future, including flight mission objective, drop location and fire characteristics at the time of the drop. Transparency in current utilisation trends helps us better target current aviation management for efficiency improvements and enables more informed evaluations of how alternative fleet compositions may alter usage.

Continued work is necessary to evaluate the effectiveness of large airtanker firefighting and, more broadly, of firefighting effectiveness in general. Similar work identifying data availability and sufficiency is necessary across the spectrum of firefighting resources and how effectiveness and resource use vary with other factors such as fire season severity and high levels of synchronous demand for firefighting resources. Analysis of airtanker trends in concert with analysis of the roles and use of other resources, in particular aviation resources that may substitute for airtankers (single-engine airtankers, scoopers, helicopters) would allow a more comprehensive evaluation of fire and aviation management.

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