

fire & fuels management

Developing an Aviation Exposure Index to Inform Risk-Based Fire Management Decisions

Crystal S. Stonesifer, David E. Calkin, Matthew P. Thompson, and Jeffrey D. Kaiden

Wildland firefighting is an inherently dangerous activity, and aviation-related accidents in particular comprise a large share of firefighter fatalities. Due to limited understanding of operational factors that lead to aviation accidents, it is unclear how local decisionmakers, responsible for requesting aviation support, can mitigate the risk of an aviation accident once resources are requested. This research expands the knowledge base regarding the quantification and analysis of aerial firefighting exposure by developing methods to evaluate expected aviation accident rates at the incident level using a metric called the aviation exposure index (AEI). Our analysis is based on coupling historical aviation accident rates (10-year average) with observed aviation resource use. As an example of the applicability of the approach, we present results according to aircraft type, unique incident, and incident jurisdiction for large wildfires that occurred during the 2012 US fire season. Ideally, the AEI could be automatically calculated and incorporated into incident decision support systems to help guide fire managers as they balance the complicated tradeoffs between attaining wildfire management objectives and reducing the exposure of individuals engaged in aerial firefighting activities.

Keywords: aviation, decision support, firefighter exposure, wildfire safety

Wildland firefighting is an inherently dangerous activity. Between 2000 and 2012, 112 federal and federally contracted wildland firefighters died in wildland fire suppression, rehabilitation, prescribed fire, or related training activities (National Wildfire Coordinating Group 2000–2012). Tragic fire events, like the loss of 19 members from the Granite Mountain Hotshots on the Yarnell Fire in 2013, highlight the need to thoughtfully consider where and when firefighters are asked to engage in wildland fire suppression actions. However, Calkin et al. (2013) demonstrated through a choice experiment

conducted in 2009 that USDA Forest Service fire managers did not consider firefighter exposure in a consistent way when making strategic suppression decisions.

In recent history, the Forest Service has been promoting risk management as the appropriate paradigm for managing wildland fires, with an increased focus on managing firefighter exposure. Along these lines, agency leadership has directed fire managers to weigh the likelihood of suppression success and avoided natural and developed resource loss achieved by suppression activities against *the type and amount of firefighter exposure to hazards* (emphasis added; Hubbard

2012, Tidwell 2013). Despite the need to address this central management tenet, there exists considerable uncertainty in assessing the likelihood of suppression actions being effective (Finney et al. 2009, Holmes and Calkin 2013), as well as the avoided losses to resources and assets impacted by fire (Thompson and Calkin 2011, Venn and Calkin 2011, Gude et al. 2013).

Along with research addressing the uncertainty of suppression effectiveness and estimation of avoided loss, research is needed to identify how best to assess and measure firefighter exposure. A prerequisite for managing firefighter safety is an understanding of which types of activities present the greatest hazard and which types of risk can be realistically mitigated. The National Wildfire Coordinating Group produces an annual Safety Gram publication that includes data for all fatalities of personnel involved in direct support of wildland fire, fire rehabilitation, transit to or from such an assignment, and training or proficiency operations in the United States.¹ Figure 1 provides a categorical summary of these fatality statistics for federal and federally contracted employees since 2000, with aviation accidents (52.7%) accounting for the largest share of fatalities (National Wildfire Coordinating

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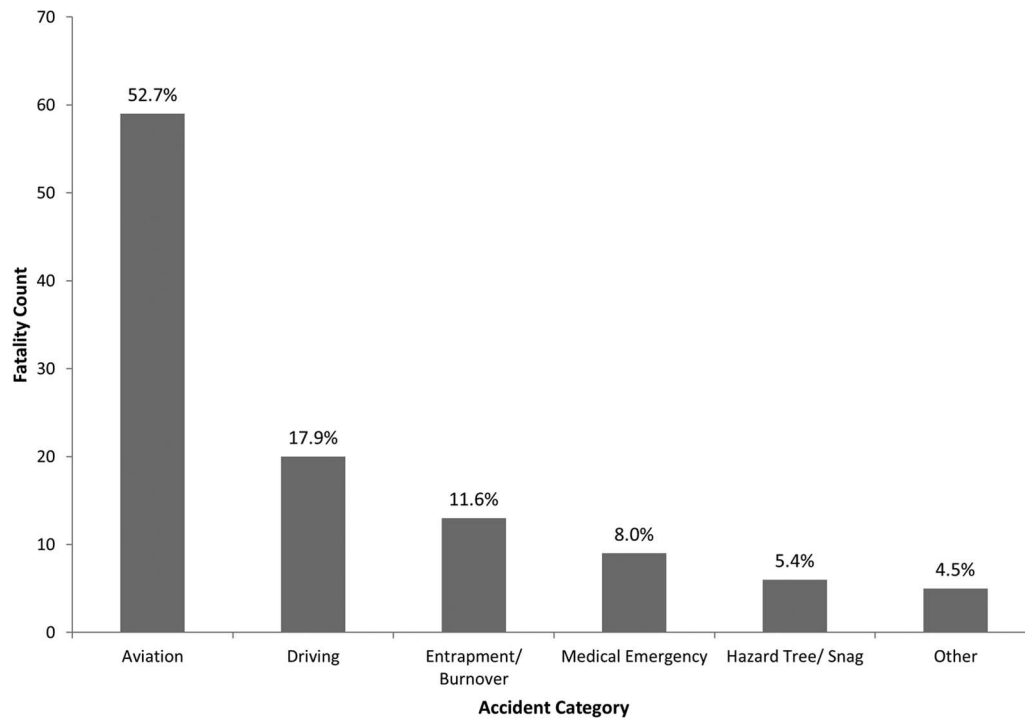


Figure 1. Federal and federally contracted firefighting fatalities, summarized by accident type from 2000–2012. Accident data were obtained from National Wildfire Coordinating Group Risk Management Committee’s annually published Safety Gram document, which records all accidents and injuries associated with wildland firefighting, training, prepositioning, and prescribed fire activities.

Group 2000–2012). Table 1 summarizes these aviation accident data by agency fiscal year (November 1 through September 30), aircraft type, mission, and number of fatalities. These data represent 29 fatal aviation accidents with 59 fatalities, and the majority of these accidents (86.2%) and fatalities (89.8%) occurred during wildland fire operations, including ferrying flights. Four accidents involving six fatalities took place during training or prescribed fire operations. Summarized by aircraft type, helicopters accounted for the greatest proportion of accidents (48.3%), followed by large airtankers (LATs; 24.1%), single engine airtankers (SEATs; 20.7%), and fixed wing aircraft (6.9%). Finally, four fatal LAT accidents involving 12 fatalities have occurred since calendar year 2004, despite implementation of stringent airworthiness standards for firefighting aircraft following two high-profile LAT accidents in 2002 and the subsequent findings presented in the Blue Ribbon Panel’s report on the safety and effectiveness of federal aerial firefighting (Hall et al. 2002).

Aviation assets play a critical role in US fire management. For example, airtankers can move quickly from place to place to reach new fires in remote, inaccessible terrain, potentially increasing the likelihood of containing a start while it is small and before it escapes initial attack. Airtankers and heli-

copters can drop water or retardant in places where it would be unsafe for ground crews to engage directly with the fireline (Figure 2). Further, small airplanes or helicopters working in aerial supervision roles can provide enhanced situational awareness with suppression personnel on the ground. Despite the potential utility, there is inherent risk in the use of any aviation asset. Once an aircraft has been requested, the ability of fire managers to mitigate a potential aviation accident appears uncertain. In a 2011 survey of Forest Service fire managers (Wibbenmeyer et al. 2013), only 37% of respondents agreed

with the statement, “Through operational risk mitigation, managers can eliminate risks of fatality to aviation personnel deployed on a wildland fire incident,” with 51% of participants generally disagreeing and 12% responding neutrally. Therefore, it appears fire managers recognize the limited feasibility of achieving the goal of zero aviation-related fatalities, even with operational risk mitigation measures in places. The only clear way to eliminate the likelihood of an aviation accident would be not to request aviation support; such an approach may result in risk being transferred to ground per-

Management and Policy Implications

In this study, we evaluate methods to estimate the expected accident rates of aviation resources on individual large wildland fires with the introduction of the aviation exposure index (AEI), using the 2012 US fire season as a test case. We propose that efforts aimed at tracking expected aviation accidents on wildland fires are consistent with recent direction from the chief of the USDA Forest Service, stating that all suppression actions should be evaluated by balancing the likelihood of suppression success and avoided natural and developed resource loss achieved by suppression activities, against the type and amount of firefighter exposure to hazards. The real-time calculation of the AEI could help individuals charged with managing large wildfires consider the level of exposure of aviation personnel to the hazards of the wildland fire environment. The approach developed here could also help managers to better consider potential risk transference between aviation and ground personnel, for instance in situations where rugged and inaccessible terrain would lead fire managers to rely more heavily on aviation resources because they deem the risk to ground personnel to be too high.

Table 1. Fatal aviation accident summary (2000–2012) for accidents in wildfire suppression, wildfire training, and prescribed fire operations involving federal and federally contracted personnel (National Wildfire Coordinating Group 2000–2012).

FY	Fire suppression operations					Training/prescribed fire operations					Yearly total
	Fixed wing	Helo	LAT	SEAT	Subtotal	Fixed wing	Helo	LAT	SEAT	Subtotal	
2000	1 (2) ^a	2 (2)		1 (1)	4 (5)	1 (1)				1 (1)	5 (6)
2001		1 (3)		1 (1)	2 (4)						2 (4)
2002		1 (1)	2 (5)		3 (6)						3 (6)
2003		2 (3)			2 (3)						2 (3)
2004		1 (1)	1 (2)	1 (1)	3 (4)				1 (1)	1 (1)	4 (5)
2005							1 (3)			1 (3)	1 (3)
2006		2 (6)			2 (6)						2 (6)
2007		1 (1)			1 (1)						1 (1)
2008		2 (10)	1 (3)	1 (1)	4 (14)						4 (14)
2009			1 (3)	1 (1)	2 (4)		1 (1)			1 (1)	3 (5)
2010					0 (0)						0 (0)
2011					0 (0)						0 (0)
2012			2 (6)		2 (6)						2 (6)
Total	1 (2)	12 (27)	7 (19)	5 (5)	25 (53)	1 (1)	2 (4)	0 (0)	1 (1)	4 (6)	29 (59)

The number of accidents and fatalities are shown by fiscal year (FY) and aircraft type (fixed wing, helicopter—helo, large airtanker—LAT, single engine airtanker—SEAT) for fire suppression and nonsuppression operations. The number of fatal accidents is presented followed by the associated number of fatalities in parentheses.

^a Number of accidents (number of associated fatalities).



Figure 2. A single-engine airtanker (SEAT) drops retardant on a wildland fire near Caliente, Nevada. Photo by Tim E. Wallace, USDA Forest Service.

sonnel and potentially increases the likelihood that the wildfire will cause resource damage.

Recent work has begun to tackle the issue of quantifying and developing performance measures for firefighter exposure. Calkin et al. (2011) developed a metric called the exposure index (EI), which is a simple measure of the amount of fire perimeter divided by the cumulative capacity of assigned resources to build, calculated over

the duration of the event. A driving rationale behind the development of the EI is that expected accident and fatality rates associated with wildland fires are likely correlated with the number of firefighters assigned and the length of time they are exposed to the wildland fire environment. The EI is essentially a measure of the productive efficiency of the management strategy of a given fire. The assumption is that if a fireline is constructed with the least possible input of re-

sources (EI approaching 100%) then firefighter exposure and potential accident rates are reduced relative to fires that have high firefighter exposure (i.e., low EI values). However, aviation missions in fire suppression are not limited to building fireline but involve a variety of objectives beyond direct suppression, such as the use of water or retardant to provide point protection of resources, transport of personnel or cargo, and aerial reconnaissance and intelligence. Therefore, because the primary objective of aviation missions may not be building fireline and because the accident rate associated with aviation is not commensurate with ground suppression activities, the EI does a poor job of considering the exposure of aviation resources.

In this paper, we introduce the aviation exposure index (AEI) as a tool for evaluating exposure and expected aviation accidents at the incident level and demonstrate the methods used to develop this index. Our analysis is focused on the 2012 fire season as a test case to introduce the AEI. The methods are based on coupling historical aviation accident rates with observed aviation resource use on large wildfire events. There are multiple challenges that come with developing a metric that characterizes aviation use and associated accident risk for fire suppression operations, particularly due to limitations in historic aviation use data and the relative infrequency of aircraft accidents. Our goal was to develop the AEI so that it has real-time utility to fire managers involved in decisionmaking related to aviation use on active incidents. Although we do not attempt to draw any inference on aviation risk trends, the information we generate will ideally help managers make the complicated tradeoffs between reducing wildfire damage and reducing the exposure of individuals engaged in aerial firefighting activities in a complex, dynamic, time-sensitive environment. Further, these data could be used to consider potential risk transference between ground and aviation resources under circumstances where these resources are being considered as potential substitutes in accomplishing an established objective. Here, we present a retrospective analysis of the 2012 fire season; however, these data and summary statistics could be generated during the active fire season to assist fire managers in their resource use decisions and facilitate improved risk-based tradeoff analyses.

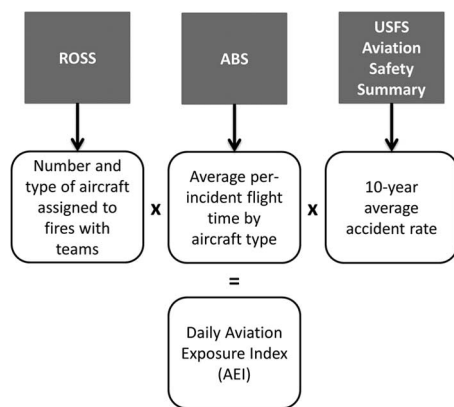


Figure 3. Flow chart for methods used to calculate the daily, per-incident, AEI from ROSS, ABS, and Forest Service historical accident rates.

Methods

Fire management in the United States is a complex multijurisdictional operation involving resources provided and accounted for by federal agencies, states, municipalities, and private entities. Thus, not all resource use and associated costs are tracked using a single system. Additionally, as discussed in Thompson et al. (2013) and Calkin et al. (2014), problems with inconsistencies in data collection methods and standards related to aviation use within existing federal data sets complicate and prevent certain analyses. Because of these issues, it is impossible to characterize historical resource use in fire suppression at wide temporal and spatial scales. Certain data systems can provide pictures of overall resource use, but some assumptions must be made regarding missing data. The National Interagency Resource Ordering and Status System (ROSS)² dispatch program data can be used to track historical resource assignments for nationally available resources and is the best available source of data for characterizing resource use at the national scale. Although ROSS does not record instances where local resources are used on a local incident, most aircraft are considered national assets; therefore, aviation use in federal fire suppression typically involves unique aircraft orders on a per-incident basis using ROSS.

To arrive at the AEI, we need to know what aviation resources are assigned to a fire, how much time those resources spend in the air, and a historical accident rate (Figure 3). We used the ROSS dispatch program data to track historical resource assignments by incident for 2012. We focused on a single

year and on the most complex incidents, those managed at some point by a type 1, type 2, or National Incident Management Organization (NIMO) team, to assess the potential utility of the AEI as a real-time risk assessment tool. To match resource use with historical accident rates, we classified aircraft resources into one of the following categories: fixed wing, helicopter, SEAT, or LAT. The fixed wing category refers to all planes that are not airtankers or water scoopers, which tend to be used for aerial reconnaissance, intelligence, communications, and personnel and cargo transport. Helicopters range in size from small type 3 aircraft that are used for suppression activities, as well as personnel and external load transport (e.g., Bell 206 variants), to large type 1 “heavy” helicopters that are used exclusively for water and retardant delivery via bucket, snorkel, or external tank (e.g., Sikorsky S-64 Skycrane). SEATs are small airtankers that can carry between 400–800 gallons of retardant (e.g., Air Tractor AT-802A), whereas LATs in the federal fleet mix, have a minimum capacity of 1,800 gallons (e.g., Lockheed P2V). Fixed wing aircraft, helicopters, SEATs, and LATs are each particularly useful for certain types of missions, although there is mission overlap in some cases (e.g., use of heavy helicopters when airtankers are unavailable).

Within ROSS the mobilization and demobilization fields associate individual aircraft to the appropriate fires for the days that they were assigned to (i.e., worked on) that incident. In the absence of accurate, readily obtained measures of cumulative flight time by incident for all aircraft, we assume aircraft worked the mean flight hours for the appropriate aircraft category on the assigned fire, estimated from the Aviation Business System query (see below).

The Forest Service used approximately 520, predominantly contract, aircraft in 2012 (USFS Fire and Aviation Management 2000–2012). Aviation Business System (ABS) is a web-based application that tracks all costs associated with these aircraft on agency-specific aviation operations. Because ABS is a Forest Service-specific program, these data exclude flights hours associated with nonagency aircraft, most notably the military C-130s equipped with Modular Airborne Firefighting Systems (MAFFS), SEATs (generally contracted by the US Department of Interior, Bureau of Land Management), the CalFire Grumman S-2T airtanker fleet, other state-owned aircraft, and

any use of Canadian aircraft. In lieu of incident-specific flight time data for nonagency aircraft, we used average per-incident flight time derived from these agency records.

ABS flight hour records are linked directly to a Forest Service financial code,³ which can be used to tie flights to large incidents. Unique fire identifiers or fire names may also be associated with flight hour records, but these inputs are not required or standardized. Because of this, ABS flight time data cannot be attributed to specific incidents in an automated fashion. To arrive at the best possible estimate of average flight time by aircraft type on large incident support, we manually matched 2012 ABS flight time data to the incidents of interest identified by the ROSS query. This time-intensive process should capture the majority of flights associated with these incidents to provide an accurate average per-incident flight time value. Given the manual processing required and the nature of ABS data collection, the total flight time by incident may be slightly underreported, particularly for initial attack (IA) operations. This is because IA flights are frequently lumped together with other IA missions for billing purposes using miscellaneous job codes.

Finally, to determine daily aviation exposure by incident, we obtained historical aviation accident rates from the Forest Service Aviation Safety Summary (USFS Fire and Aviation Management 2000–2012). These published rates are based on accidents and fatalities reported during the previous 10 years for Forest Service contract and agency-owned aircraft used for all agency missions. To calculate the AEI, accident rates are multiplied by the average daily per-incident flight time by aircraft type. We derived a daily AEI per incident by summing the corresponding exposure associated with the total aircraft assigned per incident, per day (Table 2). Although the AEI is an expectation of the number of accidents and not a probability of an accident occurring, the rarity of accidents makes this distinction insignificant (e.g., the difference between the expectation and the probability of observing one or more accidents on an event will be very small).

Aviation accidents are relatively rare, and accident statistics can vary dramatically depending on the criteria used for defining an accident, the aircraft and flight characteristics included in the summary, and the time frame used. An important component of any accident rate involves clarification of

these defining factors. Figure 4 displays annual fiscal year flight hours, accident rates, and fatality rates (USFS Fire and Aviation Management 2000–2012). Although annual accident and fatality rates exhibit considerable variability, the 10-year average accident rate appears to be relatively consistent, with the encouraging exception of the recent reduction in 2012. In contrast, the

10-year average fatality rate shows an increasing trend beginning in 2009 due to the nine fatalities associated with a helicopter accident during crew transport on the Iron Complex in California in 2008. While safety-driven modifications to the Forest Service aviation program as a whole may suggest historic averages are not consistent with current rates, we do not currently have alter-

native data sources that demonstrate a functional change in accident rates between periods of interest.

Despite programmatic changes that may result in historic accident rates overstating current accident rates, there are reasons to believe that published rates may understate incident accident rates. Published Forest Service accident rates are derived from accidents involving Forest Service aircraft on incidents with agency jurisdiction. Accident data for aircraft not contracted by the Forest Service, such as military C-130s equipped with MAFFS, are not reflected in these statistics. For example, the 2012 report shows zero accidents and fatalities despite the fact that an Air National Guard C-130 crashed on July 2 while assigned to a fire on the Black Hills National Forest, killing four of the six crew members. Accidents and flight hours associated with agency contract aircraft on non-Forest Service fires are also not included. Earlier in 2012, a two-person fatal crash of a Forest Service contract P2V occurred while conducting a retardant drop on a Bureau of Land Management (BLM) wild-fire incident; this accident was also not included in the statistics because it occurred on

Table 2. Calculation of the daily accident expectation by aircraft category (fixed wing, helicopter, large airtanker—LAT, or single engine airtanker—SEAT) from historical accident rates and the average daily flight time for a unique resource and incident assignment.

Aircraft category	Total annual flight time (hr)	Total annual unique daily incident assignments by individual aircraft	Mean daily flight time per incident (hr)	Hourly accident rate (10-yr average, 2002–2011)	Daily accident expectation
Fixed wing	13,061.7	2,930	4.46	0.0000313	0.0001396
Helicopter	23,087.8	6,798	3.40	0.0000695	0.0002363
LAT	2,084.26	655	3.18	0.0000846	0.0002690
SEAT ^a	n/a	n/a	n/a	n/a	0.0002690 ^a

Flight time and incident assignment data are from ABS records for all 2012 incidents with a corresponding type 1, type 2, or NIMO team assignment. Daily incident assignment data are from the ROSS. Mean daily flight time per incident is calculated by dividing total flight time by the number of incident assignments. Accident rates are from the USFS aviation safety summary (2011) and the daily accident expectation is calculated as the product of the mean daily flight time and the hourly accident rate.

^a SEATs are primarily owned and operated by the US Department of Interior; therefore, SEAT flight time data are not reported in ABS and accident statistics are not reported in the annual USFS Aviation Safety Summary. Given that SEATs fill similar operation roles as LATs, in the absence of raw data, we assume the same daily accident expectation as for LATs.

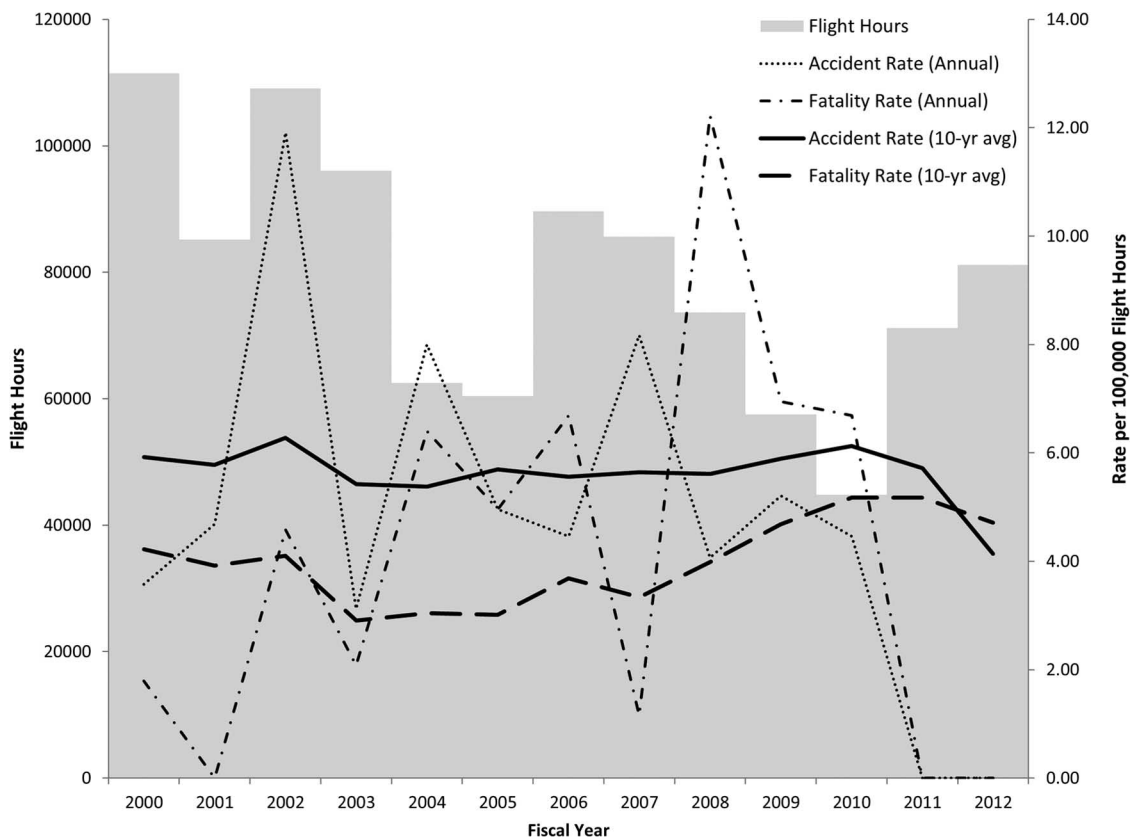


Figure 4. Forest Service fiscal year flight hours and accident and fatality rates from 2000–2012 (USFS Fire and Aviation Management 2000–2012). Aviation accident rates are shown per 100,000 hours flown, according to industry standards. The 10-year accident rate is a moving average based on data from the prior 10 years.

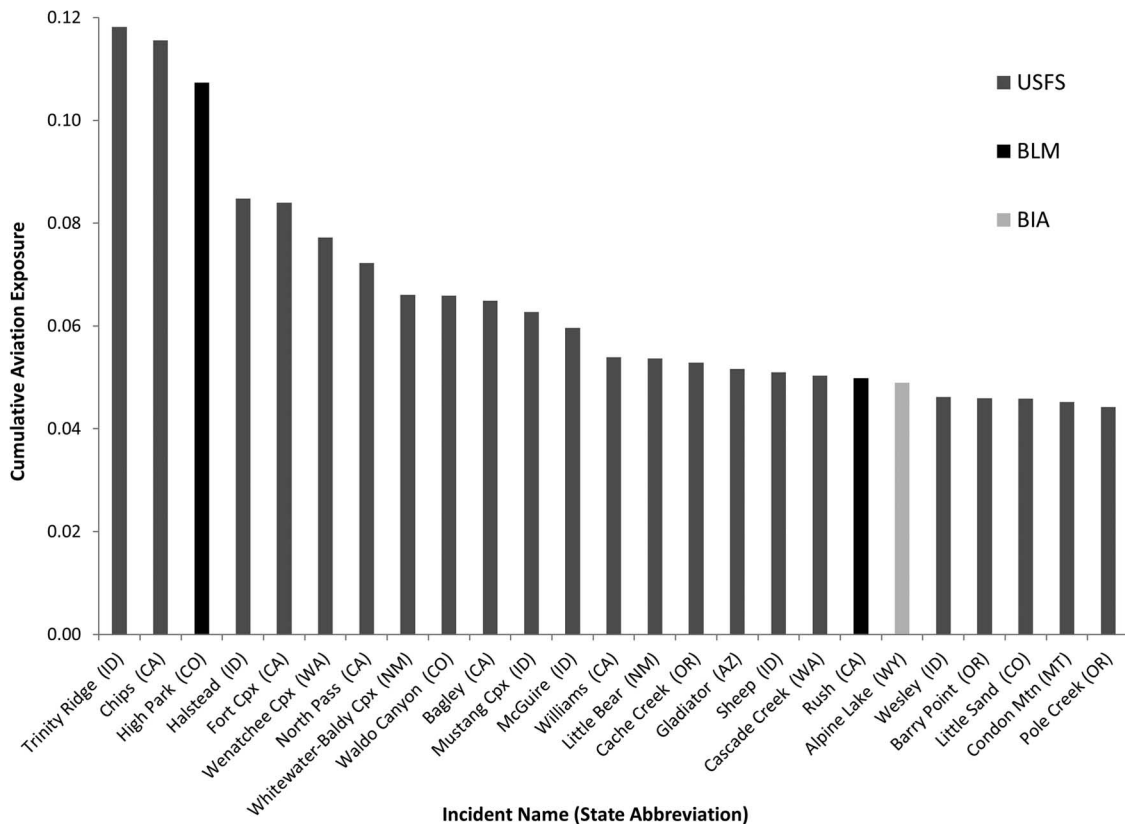


Figure 5. Cumulative aviation exposure by incident and ownership. Data are shown for the 25 fires from 2012 with the greatest cumulative aviation exposure for all aircraft use associated with each incident.

a non-Forest Service incident. We do not contend that these accident rates are intentionally misleading but instead highlight these omissions to clarify what the Forest Service Aviation Safety Summary accident rates actually reflect. Finally, it is important to note that some nonfederal entities also have aviation assets for use in fire management (notably, the state of California); flight hours and accident rates for these aircraft are tracked independently by the appropriate organization and are also not reflected in the federal rates. We use the federal Aviation Safety Summary 10-year accident rate in our calculations because it provides a standardized, widely encompassing value that can be compared against flight hour records from the same fleet of aircraft to arrive at a daily per-incident, per-aircraft accident expectation.

Results

Figure 5 displays the AEI for the 25 incidents with the highest cumulative aviation accident expectation (from a sample of 161 incidents) by incident ownership. The three fires with the greatest aviation exposure in 2012 were the Trinity Ridge Fire (0.1182), the Chips Fire (0.1156), and the High Park

Fire (0.1073). There were no reported aviation accidents on any of these three incidents, although there was a potentially serious event on the Chips Fire involving a Boeing Vertol 107 heavy helicopter when the main rotor struck a tree while lowering a bucket into a dip site (Wildland Fire Lessons Learned Center 2012). Aircraft damage was minimal, there were no associated injuries or fatalities, and it was not officially classified as an accident. In Figure 5, most of the highest aviation exposure fires were under Forest Service jurisdiction, with the exception of the High Park Fire (BLM), the Rush Fire (BLM), and the Alpine Lake Fire (Bureau of Indian Affairs). Cumulatively, there were 3.8937 expected accidents for 161 incidents included in the sample. Unfortunately, two separate aviation accidents involving six fatalities and two serious injuries occurred while aircraft were involved in fire suppression operations on an incident in this sample. First, a Forest Service contracted P2V impacted mountainous terrain after dropping retardant on a BLM fire in Nevada on June 3, 2012. Less than a month later, a military C-130 equipped with a MAFFS unit crashed while initiating a retardant

drop on a Forest Service fire in South Dakota. As previously mentioned, neither of these accidents are reflected in the 10-year average accident and fatality rates from the Forest Service Aviation Safety Summary because they do not meet the reporting criteria; one was an accident on a non-Forest Service fire, and the other involved a military asset.

Total daily aviation exposure by aircraft type for all large incidents in 2012 (defined by our sample criteria) is shown in Figure 6. The 2012 fire season was characterized by high early-season large fire activity in the Southwest, which is reflected in the dual-peaked distribution. The graph of AEI associated with pulses of fire activity for an alternate fire season may look quite different depending on the geographic and temporal patterns of seasonal fire load. Figure 6 also illustrates that helicopters consistently contributed the greatest overall aviation accident risk to incidents. Helicopters do not have the highest per-incident accident rate by aircraft type (0.0002363; Table 2), but these aircraft contribute the greatest volume of use. When summed across all days, 66.9% of the aviation accident expectation comes from helicopters, and these aircraft account

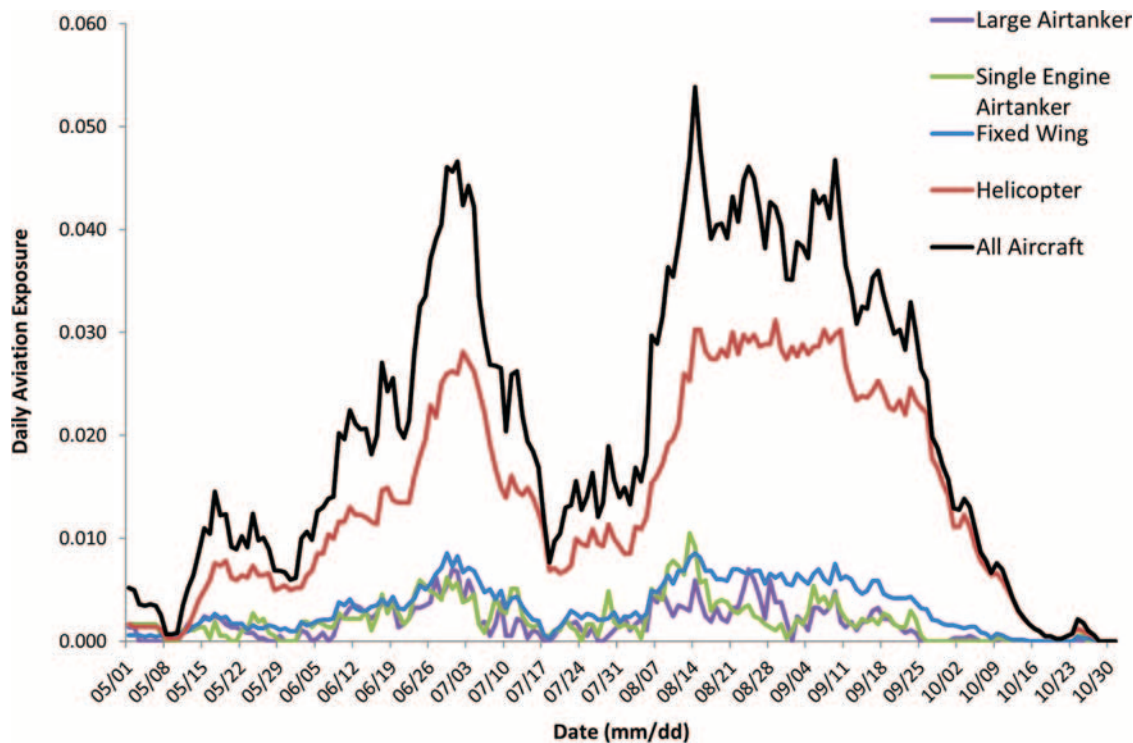


Figure 6. Total daily aviation exposure (May–October 2012) on large fire support by aircraft type. Data are shown for all aviation resources assigned to incidents managed at some point by a type 1, type 2, or NIMO team.

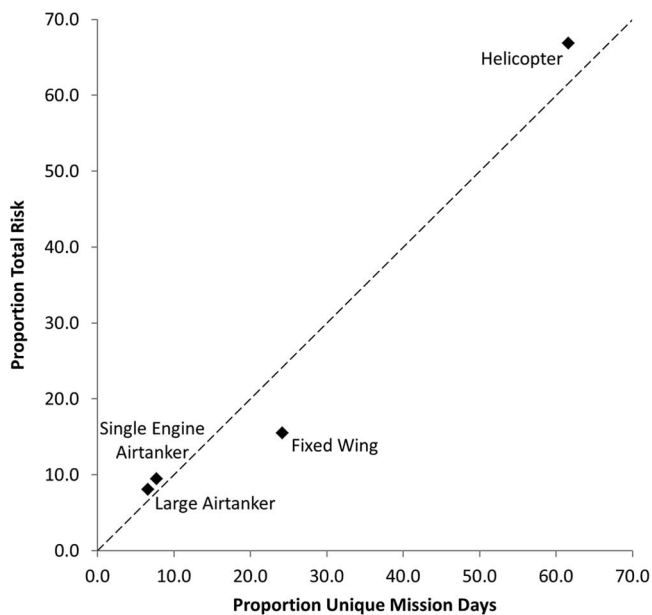


Figure 7. Cumulative aircraft accident expectation summarized by the proportion of volume of use via unique mission days (i.e., a specific aircraft on a unique fire for a certain day) by aircraft type (x-axis) and the proportion of total accident expectation by aircraft type (y-axis).

for 61.6% of the volume of use measured by unique mission days (Figure 7).

To demonstrate how daily trends in the AEI may be informative at the incident level we focus on the event with the highest cumulative AEI, the Trinity Ridge Fire. On Aug. 3, 2012, an off-road vehicle ignited a

fire on the Boise National Forest in central Idaho. This fire escaped early containment efforts, despite heavy aircraft use during initial attack, and eventually became a direct threat to the mountain resort communities of Featherville and Pine. The Trinity Ridge Fire ultimately burned 146,832 acres and

cost more than \$41 million to suppress.⁴ This incident had the highest cumulative aviation accident expectation in 2012, with 0.1182 accidents expected over the life of the incident. Figure 8 shows the daily AEI broken out by aircraft category. As observed on other high-risk Forest Service fires in 2012, the greatest aviation accident exposure came from the steady bulk of helicopter use. Consistent daily risk also comes from fixed wing aircraft, mainly associated with aerial supervision and air tactical flights. Aviation accident expectation spikes on those days where airtankers (both SEATs and LATs) are flown. The highest risk day from an aviation exposure perspective was Aug. 24, 2012, when there were four fixed wing air tactical aircraft and 14 helicopters assigned, including five type 1 heavy helicopters. For this single day and single incident, the aviation accident expectation was 0.0041. Ultimately, there were no reported aviation accidents associated with the Trinity Ridge Fire.

Discussion

Wildfire risk management requires comparison of the expected cost compared to the expected benefits of any suppression activity. Expected costs include the suppression costs as well as the probability and consequences of a bad outcome, such as an aviation accident. Further, estimating the

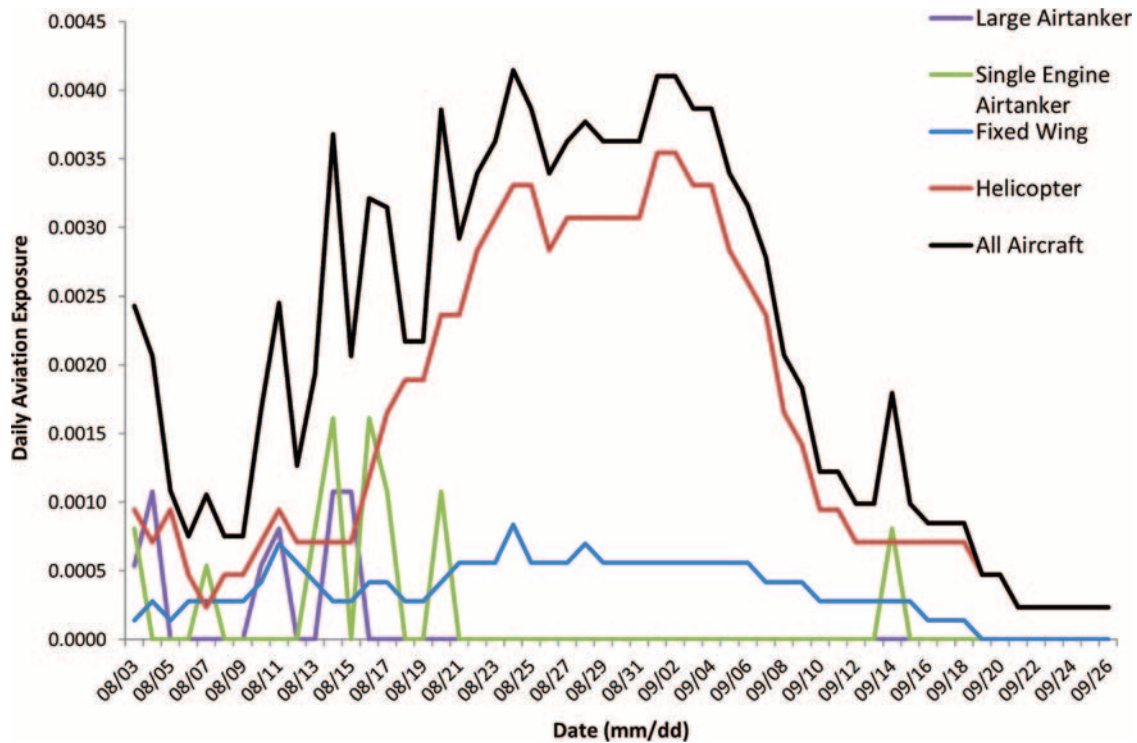


Figure 8. Daily aviation exposure by aircraft type for the Trinity Ridge Fire.

expected benefit of an action requires discounting the benefits of a suppression action (loss avoided) by the probability that the action will succeed. Articulating safety concerns within an expectation framework can be very informative and can help managers make informed, risk-based decisions on the fireline.

The Forest Service has committed to risk-informed decisionmaking within the wildland fire environment. Aviation is one of the most expensive and dangerous suppression tools available in the fire management toolkit. We found that the expected accident rates on the 25 large wildland fires with the most aviation use in 2012 all exceeded 0.044, or 4.4 accidents per 100 fires with similar aviation usage. The fire with the highest expected accident rate, the Trinity Ridge Fire, had an expectation of over 11 accidents per 100 fires. Helicopter use entailed both the highest proportion of use (61.6%) among all aviation resources and the highest contribution to total expected accident levels (66.9%).

The Forest Service reports zero accidents and fatalities attributable to agency aircraft and incidents since 2009. This is in spite of a 2012 wheels-up landing by a contract LAT working the George Fire on the Sequoia National Forest (no fatalities or serious injuries) and the previously mentioned

fatal accidents involving an Air National Guard C-130 on a fire on the Black Hills National Forest and a Forest Service contract LAT working a BLM fire on the Utah/Nevada border. Whether or not the agency's recent emphasis on improved risk-informed decisionmaking suggests that current accident rates differ from historical trends warrants additional study over a longer temporal horizon. Future research, potentially drawing on military risk-management tools for operational engagement of aviation assets, may be able to shed light on environmental and organizational factors that lead to higher accident rates. This information could be used to require additional mitigation actions on those types of activities or suggest restriction on very high-risk missions or those missions with lower expected benefits. Of particular note, the Forest Service is pursuing the next generation of LAT platforms. These newer aircraft may have reduced accident rates compared to the current fleet of Korean War-era planes, although there are several latent factors such as aircraft speed and maneuverability that will need to be evaluated. Given that aerial firefighting operations are multifaceted and include low-elevation flying in complex terrain with potential visibility issues from smoke, it is not surprising that wildfire

management aviation accident rates are far higher than commercial rates.

Current interagency aviation policies implement extensive risk-management protocols. The Interagency Standards for Fire and Aviation Operations states that "the primary means by which we prevent accidents in wildland fire operations is through aggressive risk management" (National Interagency Fire Center Federal Fire Aviation Task Group 2014, p. 07–1). To support this goal, federal agencies have multiple decision support and risk-assessment tools available to fire managers and operations personnel. For example, the Forest Service and the DOI have adopted Safety Management Systems (SMS) as the foundation of the aviation program (USFS Fire and Aviation Management 2014), which includes a risk assessment matrix to identify hazards and to develop controls to mitigate risk and make risk-based decisions. The Wildland Fire Decision Support System (WFDSS) facilitates incident-level risk assessments through various tools that help fire managers assess relative, objective measures of risk to human life and values, as well as the potential of the fire to escape containment efforts (Noonan-Wright et al. 2011). Finally, non-SMS risk assessment matrices, like the Green Amber Red (GAR) Risk Assessment Model (National Wildfire Coordinating Group

2013), provide a different format to allow decisionmakers to incorporate the effects of potentially confounding factors in their risk-based decisions (e.g., environmental factors, resource scarcity, pilot fatigue, sociopolitical pressures, etc.).

Within this risk management and decision-support framework, the agency has directed fire management personnel to make risk-based decisions that weigh the probability of success against the amount and type of firefighter exposure (Hubbard 2012, Tidwell 2013). Yet, the amount of exposure inherent in specific aviation operations has previously been an unknown. The AEI presented here provides this critical piece of information by objectively quantifying the relative risk of an accident associated with utilizing aviation resources. We do not suggest that these results are indicative of overuse of aviation resources. Rather our contention is simply that risk-informed decisions, including the concept of managing risk to the lowest practical level (USFS Fire and Aviation Management 2010), may be improved by considering these results.

Again, in this context we assume that every different aviation mission is subject to the recent historical accident rates for that platform. We recognize that different types of missions are inherently more dangerous; however, sufficient data to evaluate relative risk by mission type and environment are not currently collected. Indeed, some mission and objective information may be gleaned from financial reporting data (ABS) or from forms maintained at individual airtanker bases. Unfortunately, standardized, nationwide reporting of mission-specific information for every flight, tied to a unique incident number, does not occur. We can only reliably get information regarding mission at the time of an accident if an accident actually takes place. Furthermore, defining the effectiveness of aviation missions is challenging (McKinney 2004, Thompson et al. 2013, Calkin et al. 2014) particularly when resources are assigned to support large wildland fires. Additionally, there is a high level of uncertainty of outcomes with respect to suppression operations (Thompson and Calkin 2011). A primary challenge on large fires is the fact that the objective of an aviation mission can be wide ranging, as previously discussed, and there are likely multiple potential objectives under each mission type. Currently, no records are collected by US federal agencies that both identify a spe-

cific aviation mission objective and assess the outcome of the specific action.

Plucinski and Pastor (2013) lay out a framework for identifying the effectiveness of airtanker drops in achieving specified missions. Similarly, research is currently underway in the United States involving field observations of aviation use in fire suppression to improve our understanding of both the types of missions that aviation resources engage in, as well as their effectiveness in achieving the specified mission objectives (Aerial Firefighting Use and Effectiveness Study). Areas of promising future research include both the evaluation of the cost and benefits of suppression resource use, as well as the relative tradeoffs or complementarity in terms of effectiveness, cost, and accident rates among different suppression resource categories (e.g., ground crews versus aviation, heavy helicopters versus LATs). Simple improvements to existing data collection systems, including standardization and synthesis of recordkeeping at airtanker bases, and systemwide use of the Unique Fire Identifier⁵ to link records of all types directly to a specific incident would greatly enhance our ability to characterize aviation use and to potentially refine calculations of associated risk.

In this paper, we introduced the AEI as a tool to facilitate risk-based fire management decisionmaking and demonstrated the potential utility of the AEI in this capacity through a retrospective analysis focused on the 2012 fire season. Through this, we identified a potential role for this metric to inform risk-based decisionmaking. Because this metric has not been available before, we are unsure of its effect on the decisionmaking processes of incident-level fire managers; however, the AEI addresses a critical need to provide an objective measure of aviation risk inherent with a specific level of aviation asset utilization. This will facilitate an informed dialogue at the incident level regarding mission objectives, probability of success, and associated risk. Further, the AEI may allow upper-level fire managers to exercise controls on aviation use for incidents that fail to demonstrate defensible justification for a high amount of aircraft utilization (e.g., an incident with high relative aviation exposure that also has low relative risk to highly valued resources). Consequently, through our methods we also identified significant data collection needs, which if addressed, would enhance our ability to refine exposure indices so that they reflect mission-specific avia-

tion resource use. Beyond the utility of the AEI as a decision-support tool, historical calculations could provide value to the learning component of the formal risk-management process through the identification of potential high-risk trends or patterns of aviation use. Ultimately, it is our hope that this index can assist fire managers in safely achieving fire management objectives with the least firefighter exposure necessary.

Endnotes

1. For more information, please visit www.nwcg.gov/branches/pre/rmc/safety-grams/safetygram_criteria.pdf.
2. For more information on ROSS, please see www.ross.nwcg.gov.
3. For more information concerning the USDA/DOI FireCode system, please visit www.firecode.gov/help/User_Guide.pdf.
4. Please see www.predictiveservices.nifc.gov/intelligence/2012_statsumm/wildfire_charts_tables.pdf for more information.
5. Please visit www.nwcg.gov/pms/stds/standards/unique-fire-identifier_v1-0.htm for more information.

Literature Cited

- CALKIN, D.E., J. PHIPPS, T.P. HOLMES, J. RIECK, AND M.P. THOMPSON. 2011. The exposure index: Developing firefighter safety performance measures. *Fire Manage. Today* 71(4):24–27.
- CALKIN, D.E., T. VENN, M. WIBBENMEYER, AND M.P. THOMPSON. 2013. Estimating US federal wildland fire managers' preferences toward competing strategic suppression objectives. *Int. J. Wildl. Fire* 22(2):212–222.
- CALKIN, D.E., C.S. STONESIFER, M.P. THOMPSON, AND C.W. MCHUGH. 2014. Large airtanker use and outcomes in suppressing wildland fires in the United States. *Int. J. Wildl. Fire* 23(2):259–271.
- FINNEY, M.A., I.C. GRENFELL, AND C.W. MCHUH. 2009. Modeling containment of large wildfires using generalized linear mixed-model analysis. *For. Sci.* 55(3):249–255.
- GUDE, P.H., K. JONES, R. RASKER, AND M.C. GREENWOOD. 2013. Evidence for the effect of homes on wildfire suppression costs. *Int. J. Wildl. Fire* 22(4):537–548.
- HALL, J.E., J.B. HULL, K. JOHNSON, E.H. MCKINNEY, AND W.B. SCOTT. 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 online at www.fs.fed.us/fire/publications/aviation/fed_aerial_ff_assessing_safety_effectiveness_brp_2002.pdf; last accessed Apr. 1, 2014.
- HOLMES, T.P., AND D.E. CALKIN. 2013. Econometric analysis of fire suppression production functions for large wildland fires. *Int. J. Wildl. Fire* 22(2):246–255.

- HUBBARD, J. 2012. 2012 Wildfire guidance. Available online [http://documents.fusee.org/AMR/Hubbard memo 5-25-12.pdf](http://documents.fusee.org/AMR/Hubbard%20memo%205-25-12.pdf); last accessed Apr. 1, 2014.
- McKINNEY JR., E.H. 2004. Learning by fire: The learning challenges facing US Forest Service aviation. *Govt. Information Qtrly.* 21(1):86-98.
- NATIONAL INTERAGENCY FIRE CENTER FEDERAL FIRE AVIATION TASK GROUP. 2014. Interagency standards for fire and fire aviation operations. Available online at www.nifc.gov/PUBLICATIONS/redbook/2014/RedBookAll.pdf; last accessed July 1, 2014.
- NATIONAL WILDFIRE COORDINATING GROUP. 2000-2012. Safety gram. Available online at www.nwgc.gov/branches/pre/rmc/safety-grams/sg-archive/safety-gram-archive.htm; last accessed Apr. 1, 2014.
- NATIONAL WILDFIRE COORDINATING GROUP. 2013. Interagency helicopter operations guide. Available online at www.nwgc.gov/pms/pubs/pms510/00_pms510.pdf; last accessed July 7, 2014.
- NOONAN-WRIGHT, E.K., T.S. OPPERMAN, M.A. FINNEY, G.T. ZIMMERMAN, R.C. SELI, L.M. ELENZ, D.E. CALKIN, AND J.R. FIEDLER. 2011. Developing the US Wildland Fire Decision Support System. *J. Combust.* 2011 (168473). doi: 10.1155/2011/168473.
- PLUCINSKI, M.P., AND E.P. PASTOR. 2013. Criteria and methodology for evaluating aerial wildfire suppression. *Int. J. Wildl. Fire* 22(8): 1144-1154.
- THOMPSON, M.P., AND D.E. CALKIN. 2011. Uncertainty and risk in wildland fire management: A review. *J. Environ. Manage.* 92(8): 1895-1909.
- THOMPSON, M.P., D.E. CALKIN, J. HERYNK, C.W. MCHUGH, AND K.C. SHORT. 2013. Airtankers and wildfire management in the US Forest Service: examining data availability and exploring usage and cost trends. *Int. J. Wildl. Fire* 22(2):223-233.
- TIDWELL, T. 2013. Chief's letter of intent—2013 fire season. Available online at [www.pearce.house.gov/sites/pearce.house.gov/files/Chiefs Letter of Intent.pdf](http://www.pearce.house.gov/sites/pearce.house.gov/files/Chiefs%20Letter%20of%20Intent.pdf); last accessed Apr. 1, 2014.
- USFS FIRE AND AVIATION MANAGEMENT. 2000-2012. FY aviation safety summary. Available online at www.fs.fed.us/fire/av_safety/assurance/fy_safety_reports; last accessed Apr. 1, 2014.
- USFS FIRE AND AVIATION MANAGEMENT. 2010. 2011 National Aviation Safety and Management Plan. Available online at www.fs.fed.us/fire/aviation/av_library/2011%20National%20Aviation%20Safety%20and%20Management%20Plan.pdf; last accessed Apr. 1, 2014.
- USFS FIRE AND AVIATION MANAGEMENT. 2014. Aviation Safety Management System guide. Available online at www.fs.fed.us/fire/av_safety/policy/FS_SMS_Guide_2014.pdf; last accessed July 7, 2014.
- VENN, T.J., AND D.E. CALKIN. 2011. Accommodating non-market values in evaluation of wildfire management in the United States: Challenges and opportunities. *Int. J. Wildl. Fire* 20(3):327-339.
- WIBBENMEYER, M.J., M.S. HAND, D.E. CALKIN, T.J. VENN, AND M.P. THOMPSON. 2013. Risk preferences in strategic wildfire decision making: A choice experiment with US wildfire managers. *Risk Analysis* 33(6): 1021-1037.
- WILDLAND FIRE LESSONS LEARNED CENTER. 2012. Chips fire helicopter rotor blade strike. Available online at <http://wildfirelessons.net/communities/resources/viewincident/?DocumentKey=4f820f1d-a386-4d6a-b01e-dd427e520e84>; last accessed Apr. 1, 2014.