CSIRO PUBLISHING

International Journal of Wildland Fire **2017**, *26*, 604–614
http://dx.doi.org/10.1071/WF17054

Characterising resource use and potential inefficiencies during large-fire suppression in the western US

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Abstract. Currently, limited research on large-fire suppression effectiveness suggests fire managers may over-allocate resources relative to values to be protected. Coupled with observations that weather may be more important than resource abundance to achieve control objectives, resource use may be driven more by risk aversion than efficiency. To explore this potential, we investigated observed percentage of perimeter contained and self-reported containment values, the exposure index, and patterns of resource use during the containment and control phases of fire response. Fireline production capacity of responding resources typically exceeds final fire perimeter, often by an order of magnitude or more. Additionally, on average, 21% of total incident resource productive capacity was observed on the fire during the control phase, that is, after the fires cease to grow. Our results suggest self-reported percentage containment significantly underestimates actual percentage of perimeter contained throughout an incident, with reported values averaging only 70% contained at actual fire cessation. Combined, these results suggest a fire manager's risk perception influences resource use and may unnecessarily expose responders to fireline hazards. These results suggest a considerable opportunity to improve large-fire management efficiency by balancing the likelihood and consequences of fire escape against the opportunity cost of resource use.

Additional keywords: firefighting, large fire management, percentage contained, suppression resource effectiveness.

Received 15 July 2016, accepted 16 June 2017, published online 10 July 2017

Introduction

Today's wildfire environment has become increasingly complex and hazardous as a result of unanticipated consequences of historical forest and fire management, a rapidly changing climate and an increasingly populated wildland urban interface (Haas *et al.* 2013; Stephens 2014; Jolly *et al.* 2015). The United States interagency fire management community remains effective at suppressing 95–98% of wildfires during initial attack (IA) (Strauss *et al.* 1989; Calkin *et al.* 2005). Yet, the low percentage of escaped fires, which account for ~95% of annual area burned, have resulted in increasing fire extent (Littell *et al.* 2009) and expanding direct federal fire management expenditures that regularly exceed \$1.5 billion annually in the United States (US) alone (Fig. 1). Further, from 1995 to 2014 wildfires accounted for >\$10 billion of ensured losses (Munich 2017). Fatalities and injuries continue to mount during wildfire management (National Interagency Fire Center 2017), and current policies and actions are not leading to or maintaining resilient landscapes (Stephens *et al.* 2016).

Together these factors suggest our current approach to wildfire management may not represent the most effective long-term approach for achieving the fire management goals of: 1) resilient landscapes; 2) fire-adapted communities; and 3) safe and effective wildfire response established under the National Cohesive Wildland Fire Management Strategy (NCWFMS) (Wildlands Fire Leadership Council 2012). Fire-prone landscapes and the policies governing their management are integrated in a complex social ecological system composed of exogenous and endogenous influences with multi-scale interactions and feedbacks, making the consequences of policy or management changes difficult to predict (Spies *et al.* 2014; Steelman 2016). Research and management efforts have primarily focused on social perceptions, creating fire adapted communities and hazardous fuels reduction strategies (Moritz *et al.* 2014; North *et al.* 2015). The fire management sub-system has received less attention by the research and management community despite the potential for it to have undue influence over NCWFMS goals (Thompson *et al.* 2015). We believe that directly investigating the efficiency of wildfire management is both prudent and necessary for achieving national wildfire management priorities, especially concerning safe and effective wildfire response.

Wildfire management is a complex undertaking requiring managers to balance the investment of suppression resources against the potential losses avoided due to their suppression actions. On large wildland fires this requires estimating potential fire spread for days or weeks into the future, the response of a multitude of resources exposed to wildfire across space and

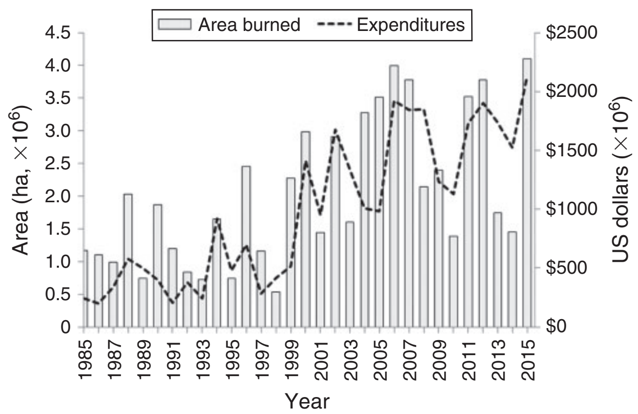

Fig. 1. Total area burned and total direct federal expenditures on wildland fire management in the United States.

time, and the likelihood that any given suppression effort will either stop fire spread or reduce adverse effects on valued resources. Substantial uncertainty exists in all these factors (Calkin *et al.* 2010; Scott *et al.* 2013; Duff and Tolhurst 2015) and to date there has been limited effort to define an economically efficient strategic response for large fires.

Research investigating the selection of preferred fire management strategies suggests fire managers may over-allocate resources even when the risk of escape is low (Wibbenmeyer *et al.* 2013), fire weather may be more important than number of resources to achieve control objectives (Finney *et al.* 2009), and resources may be commonly used outside their intended priorities (Stonesifer *et al.* 2014). For example, mission priority for air tankers is IA (USDA Forest Service 2011), but a series of studies have concluded that large air tankers are extensively used during extended attack and on large fires, often during times of highest fire spread potential and lowest operational effectiveness (Thompson *et al.* 2013; Calkin *et al.* 2014; Stonesifer *et al.* 2016). These studies suggest there may be opportunities to improve wildfire management by reducing costs and limiting responder exposure to hazards other than those necessary to achieve response objectives.

Several factors affect the combination and pattern of resources employed during suppression of large fires. In addition to weather and expected fire behaviour, social, psychological and institutional factors may also affect decision making and use of suppression resources (Calkin *et al.* 2013; Thompson 2014). Fire managers' risk perceptions are important determinants of manager decisions and are associated with suppression expenditures (Canton-Thompson *et al.* 2008). Accordingly, fire managers may have different preferences towards managing fires based on their experience and risk perception, and patterns and mix of resource use may vary during different stages of an incident. Thus, there is a strong interest and need to investigate the combination and pattern of resources employed during different stages of large wildfire suppression.

The purpose of this study is to explore resource use and effectiveness on large fires throughout the duration of the incident, and to highlight any evidence of potential inefficiencies given generally limited data availability. We focus on: (1) incident level productive capacity of all resources relative to length of fire perimeter; (2) resource abundance during the active growth and control phase as delineated by actual fire cessation; (3) the types of resources used during these phases of fire management; and 4) the relationship between the daily observed percentage of final fire perimeter contained and the reported percentage containment during an incident. We follow these results with an expanded discussion on the state of knowledge regarding resource use and potential inefficiencies during large-fire management. Our observations are discussed within the context of economic theory in the interest of better understanding, and potentially improving large fire management.

Methods

Data sources

We integrated large-fire management data from various sources in this study. Resource information came from the Resource Order and Status System (ROSS). ROSS is a comprehensive database tracking tactical, logistical and support resources mobilised to wildland fire incidents in the US. Information on the fire status was obtained from incident command system situation (ICS-209) reports. ICS-209 reports provide information on fire status, daily fire size and percentage containment, as estimated by the incident management team (IMT) or managing agency using a variety of methods such as helicopter reconnaissance, fixed-wing infrared mapping and ground based reconnaissance (Finney *et al.* 2009). These reports are required for all incidents managed under a full suppression strategy that are >40 ha in extent in timber fuel types or >121 ha in grass and shrubs fuel types, as well as any incident managed by a Type 1 or Type 2 IMT regardless of size (Thompson 2013). Type 1 and Type 2 IMTs are national and state level resources. A Type 1 IMT is the IMT with the most training and experience. A Type 2 IMT is the team with less training and experience than Type 1 IMT. We excluded aircraft without retardant or water delivery systems (e.g. reconnaissance and smokejumper aircraft) because they are not directly used for control line production or support.

We quantified the daily growth of incidents using geospatial fire progression data retrieved from the Wildland Fire Decision Support System (http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml, accessed March 2014), National Interagency Fire Center (NIFC) fire reports, and Geospatial Multiagency Coordination website (http://www.geomac.gov/, accessed March 2014). Only fires larger than 121 ha were included in our analyses. We excluded fires managed as complexes (i.e. multiple fires managed as one incident) because of ambiguity in resource allocation among the multiple fires managed within the complex. Table 1 provides a summary of the fires included in our analyses. After assessing data quality, we had 125 large fires from 2010 to 2012. These large fires covered multiple vegetation types across much of the western US (Fig. 2). A detailed discussion of data collection, screening and cleaning processes are available in Katuwal *et al.* (2016).

Information on percentage contained is one of the most frequently used indicators of the management status of an active large fire. The National Wildfire Coordinating Group defines containment as 'the status of a wildfire suppression action signifying that a control line has been completed around the fire, and any associated spot fires, which can reasonably be

Table 1. Summary statistics of the fires used in our analyses

Year	Number of fires	Final area (ha) Mean (min., max.)	Number of days until observed fire cessation Mean (min., max.)	Number of days until fire are reported 100% contained Mean (min., max.)
2010	23	3076 (190.2, 18 170)	18.52 (3, 113)	45.7 (4, 122)
2011	38	8071 (185.4, 90 240)	23.45 (3, 91)	45.08 (6, 127)
2012	64	11 070 (140.2, 120 500)	17.98 (2, 70)	35.75 (5, 122)
All	125	8690 (140.2, 120 500)	19.74 (2, 113)	40.42 (4, 127)

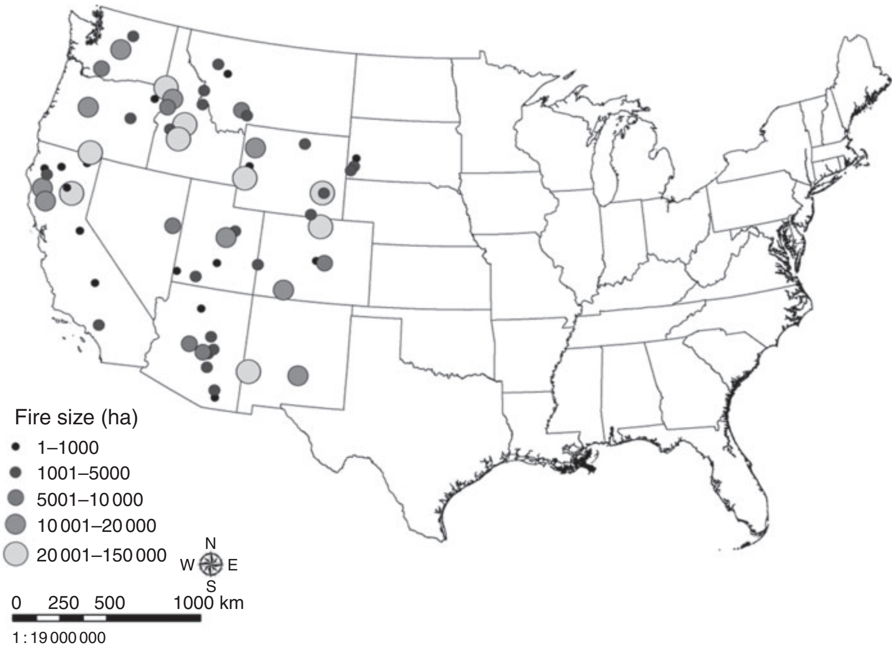

Fig. 2. Map of the geographic location of fires included in our analyses.

expected to stop the fire's spread' (National Wildfire Coordinating Group 2017). Operationally, percentage contained should reflect the amount of current fire perimeter with a completed control line that may or may not have ongoing mop up activities as responding resources continue extinguishing the fire until declared controlled or out. Here, we report line as contained as soon as the fire reaches a point that ultimately resides along the final fire perimeter. We recognise field personnel may delay reporting line as contained until there is some level of assurance that the fire will not spread beyond the line; a decision we wish to highlight. The time between fire ignition and actual fire cessation defines the containment phase, and the time between fire cessation and reported 100% containment (in ICS-209 forms) as the control phase in our analyses.

Data analysis

We examined total incident resource production capacity relative to estimated need during large-fire management beginning from ignition to the end of the control phase using the exposure index (Calkin *et al.* 2011). The exposure index provides a basic assessment of efficiency by comparing the total line productive capacity of all resources assigned throughout the incident to the length of fireline construction required, as indicated by the final fire perimeter. Exposure index is an internal performance metric for all large fires reported through the Risk Console (RisC) used by US federal fire management agencies. Production rates for individual resources were used to compute total productive capacity of all responding resources (e.g. handcrews, bulldozers, fire engines, helicopters) assigned until the end of the control phase (Broyles 2011; Holmes and Calkin 2013). Calkin *et al.* (2011) essentially argued that the quantity of firefighter exposure to hazards relates inversely to the productive efficiency of resources used. A low exposure index value may be an indication of inefficient resource use, ineffective fireline construction and unnecessary exposure of responders to operational hazards.

Our second analysis explored resource use during large fire management by examining differences between the containment and control phases. First, we quantified the proportion of total incident productive capacity allocated to each phase. ROSS provided the number of major suppression resources (handcrews, bulldozers, fire engines, helicopters and air tankers) for each day of each incident. Again, published control line production rates were used to evaluate all resources on a common scale

(Broyles 2011). We divided our sample into categories of equal number of fires (tertiles) based on final fire size and numbers of days until the end of the control phase, to examine if resource use by phase was associated with these factors. Large air tankers were not included in this analysis because they lack empirically derived production rates. However, we augmented this analysis by investigating variations in resource use by type during the containment and control phases using the number of resource assignments (e.g. number of fire engine assignments) instead of production capacity so that we could include air tankers.

We investigated potential inefficiencies in resource use by focusing on resource packages used during the containment and control phases. We define resource packages as the distribution of productive capacity across handcrews, mechanised equipment, fire engines and helicopters relative to the total available productive capacity. For this analysis, total available productive capacity was the summation of productive capacity within a given phase thereby providing a relative comparison of resource packages on the same scale given changes in absolute differences by management phase. Resources conducting mop-up or rehabilitation activities following the control phase were not included in our analyses.

We further explored potential inefficiencies in fire management by quantifying the relationship between actual daily percentage of final fire perimeter contained and the reported percentage contained from the ICS-209 forms. This provides an assessment of whether regional or national-scale fire management planning or other economic efficiency analyses can rely on self-reported information at the incident-level. Our intent was not to draw inference about factors that may contribute to variation in reported *v.* actual percentage containment, but rather understand how accurate these reported values were across the full containment phase. We did not have any expectation of the underlying relationship (i.e. linear or non-linear) between these two values so we used a generalised additive mixed-model to evaluate the relationship between reported percentage containment and actual percentage perimeter containment across all days within our sample. Specifically, these models offer a robust test of potentially non-linear relationships. A total of 1482 daily observations from 119 fires with >3 days before 100% containment were used in this analysis. We used default thin plate regression splines (Wood 2003), a Gaussian distribution with an identity link, and included the random effects term (fire name) for the lack of independence in observations from a single fire event.

We expanded upon the previous analysis by estimating the reported percentage contained at the time of actual fire cessation, as well as the time elapsed between cessation and reporting of 100% containment. This analysis required consistently reported information on percentage contained until fire cessation, leaving only 99 out of 125 fires for inclusion.

Results

A total of 93 fires, managed under a full suppression strategy, were used to estimate incident-level exposure index (EI). On average, three times (EI = 0.30) the amount of resource line production capacity was used on these fires than estimated to be necessary to construct fireline around the observed final perimeters (Fig. 3). The exposure index ranged from EI = 0.02 (50 times the amount of resource capacity necessary for line construction) to EI = 1.75 (57% of estimated production capacity necessary to construct the final fire perimeter). We did not find a statistical correlation between the proportion of total productive capacity used during the containment phase (described below) and the exposure index (Pearson correlation $r = 0.05$; P-value = 0.62). These results suggest there is inefficient resource use, although the actual amount of resources necessary for line construction are difficult to address given the range of conditions responding resources encounter.

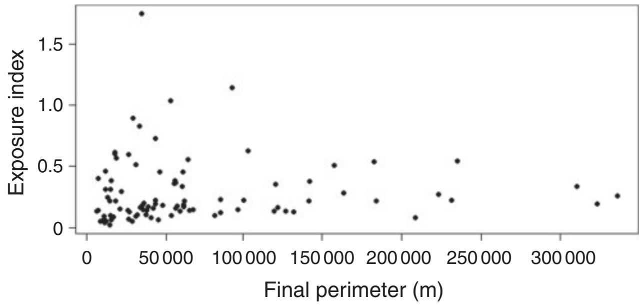

Fig. 3. Incident exposure index for 91 fires (>121 ha) in the western US. Two fires with final perimeter exceeding 400 000 m were removed to allow for improved resolution for the majority of the data.

The duration of the containment and control phases, as well as allocation of resource productive capacity by phase, varied considerably across our sample. On average, the containment phase lasted 20 days with an additional 20 days until reported as 100% contained (i.e. control phase). We found that on average 79% of total incident resource productive capacity occurred during the containment phase (Table 2). Only 15% of the fires utilised 100% of their productive capacity during this phase, with an additional 40% (50 of the 125 fires) using 90% of their productive capacity during this phase (Fig. 4). On the other hand, more than 50% of total resource production capacity occurred during the control phase for 9% (11 of 125) of the fires. We observed proportionately more resource production capacity during the control phase on smaller-sized incidents, as well as those that burned for short periods (Table 3). Analysis of variance results suggest that the mean of the resource capacity assigned to different size fires are not all equal (Table 4). Although the average production capacity allocated during control phase for fires in the smallest size group (group 1) was not statistically different from the production capacity allocated for the fires in the medium size group (group 2), the difference was statistically significant ($P = 0.049$) when compared to the largest size group (group 3). For example, on average ~15% of total resource production capacity occurred during the control phase on the larger incidents as compared to 25% on the smaller fires. We also observed ~10% of resource production capacity assigned after the containment phase on the group of longest duration fires, compared to ~28% for the group of shortest duration fires. Analysis of variance based on duration of the active fire results suggest that the mean of the resource capacity assigned to different duration fires are not all equal (Table 5). The average allocation of resources during the control phase for

Table 2. Percentage of resource capacity assigned until fires stop growing

Year	Number of fires	Percentage of productive capacity assigned until fires stop growing		
		Mean	Median	s.d.
2010	23	73.42	80.84	23.13
2011	38	82.08	87.55	18.03
2012	64	79.56	85.15	18.12
All	125	79.19	85.19	19.17

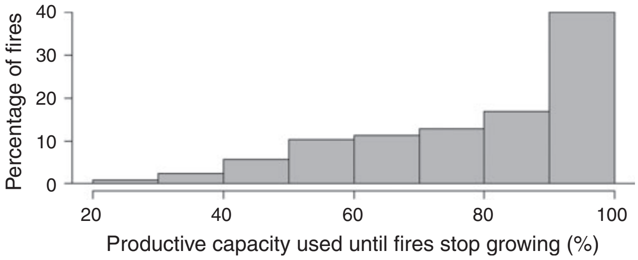

Fig. 4. Distribution of productive capacity and percentage of fires before actual fire cessation for large fires in the western US.

the fires in the medium duration group (group 2) and shortest duration group (group 1) were statistically significantly greater than the resource capacity allocated to fires in the longest duration group fire (group 3).

Fire managers retained or acquired all types of suppression resources for the control phase, although the number of assignments was lower than during the containment phase (Fig. 5). This included a substantial amount of aviation resources; on average, 18 and 9% of total incident assignments for helicopters and air tankers respectively occurred during the control phase. Relative to other resources, fire managers retained a larger percentage of total resource assignments for fire engines (23%) during the control phase. However, most resources had similar proportions of their assignments retained or allocated to each management phase.

Self-reported percentage containment significantly underestimated actual percentage of final fire perimeter contained (Fig. 6, Table 6). The smoothing spline fit from the generalised additive mixed-model was significant at an $\alpha \leq 0.05$ ($F = 613.5$, approximate P-value < 0.0001, estimated degrees of freedom $= 6.162$). We observed a non-linear relationship between reported *v.* actual fire containment, such that reported containment was similar to actual containment for fires <10% contained, at which point reported containment values deviated significantly and persisted to actual fire cessation (Fig. 6). We observed the greatest departure from 20 to 80% of actual containment, where reported containment averaged ~45% lower than actual containment. Thereafter, reported containment was closer to actual containment but was still 30% lower at time of actual fire cessation. Reported values were highly inconsistent throughout the containment phase as observed by the variation in Fig. 6.

Reported containment averaged 70% on large fires at the time of fire cessation (Table 7), but this estimate varied widely across the fires in our sample (Fig. 7). Only 9% of the incidents reported 100% containment at observed fire cessation, with 43% (46 of 99) reporting ≥80% containment at this time. One explanation for this discrepancy might be the difficulty of accurately assessing perimeters across broad landscapes, which depends in part on the experience of those making the estimates. We examined if this was likely the case by comparing final burned area reported in the ICS-209 and the burned area obtained from geospatial data the day fires reached maximum burned area. Our result indicated that burned areas reported by the fire managers in the ICS-209 and areas calculated from our geo-spatial data were almost identical (Pearson correlation $r = 0.9999$). Fire mangers clearly have the experience and capability to predict fire area accurately, indicating they could quantify the percentage of fire perimeter with a fireline more accurately and in accordance with the National Wildfire Coordinating Groups definition.

We did not observe statistically significant variation in resource packages used during the containment and control phases ($P > 0.85$ for all resource types). That is, the relative abundance (ratio of production capacity of one resource type to production capacity of all resource type) of handcrews, fire engines, dozers and helicopters did not differ by management phases despite the potential for tactical objectives and assignments to change (Fig. 8). However, absolute numbers of resources decreased significantly as the fires transitioned from the containment to control phase. This analysis did not include air tankers because we relied on resource productive capacity to compare across different resources. Based on the percentage of assignments by resource and management phase, we would expect a decrease in the retention or use of air tankers during the control phase relative to other resources. This was evident in air tankers having a higher percentage of total assignments during the containment phase relative to the other resources (Fig. 5).

Discussion

Agency-wide budgetary constraints, the increasingly hazardous operational environment and resource scarcity have elevated the need for improved efficiency in resource use on large fires (Duff and Tolhurst 2015). Applying economic theory and analyses to large-fire management problems, such as production theory, has the potential to highlight inefficiencies and improve response (Mendes 2010). From this perspective, fire suppression is a production process whereby resources produce fireline to delay and contain a spreading fire. The exposure index provides an incident-scale assessment of resource production effectiveness relative to a theoretical maximum. Our assessment from large fires in the western US suggests that on average three times as

Table 3. Percentage of resource capacity assigned until fires stop growing for different size and different duration fires
Size group: 1 indicates group of smallest fires; 3 the group of largest fires. Duration group 1 indicates group of shortest duration fires; 3 the group of longest duration fires. Fire duration is based on total number of days until fires are reported 100% contained in ICS-209

Size and duration group	Number of fires	Percentage of productive capacity assigned until fires stop growing (size group)	Percentage of productive capacity assigned until fires stop growing (duration group)
1	42	75.02	71.94
2	42	77.83	76.06
3	41	84.87	89.83
All	125	79.19	79.19

Table 4. ANOVA results for the percentage of resource capacity assigned until fires stop growing for different size fires
Probabilities are significant at: ***, $0 < P < 0.01$; **, $0.01 < P < 0.05$; *, $0.05 < P < 0.1$

	d.f.	Sum Squares	Mean Square	F-value	Pr(>F)
Between groups	2	2132	1066.1	2.993	0.0538
Residuals	122	43459	356.2		
Tukey multiple comparisons of means (90% group-wise confidence level)					
	Mean difference	lower	upper		P adjusted
group 2 – group 1	2.8055	−5.727	11.338	0.7748	
group 3 – group 1	9.8521**	1.2673	18.437	0.0493	
group 3 – group 2	7.0466	−1.538	15.631	0.2091	

Table 5. ANOVA results for the percentage of resource capacity assigned until fires stop growing for different duration fires
Probabilities are significant at: ***, $0 < P < 0.01$; **, $0.01 < P < 0.05$; *, $0.05 < P < 0.1$

	d.f.	Sum Squares	Mean Square	F-value	Pr(>F)
Between groups	2	7257	3629	11.55	0.0000
Residuals	122	38334	314		
Tukey multiple comparisons of means (90% group-wise confidence level)					
	Mean difference	Lower	upper		P adjusted
group 2 – group 1	4.1175	−3.8965	12.1314	0.5379	
group 3 – group 1	17.8855***	9.8228	25.9482	0.0000	
group 3 – group 2	13.7680**	5.7053	21.8307	0.0016	

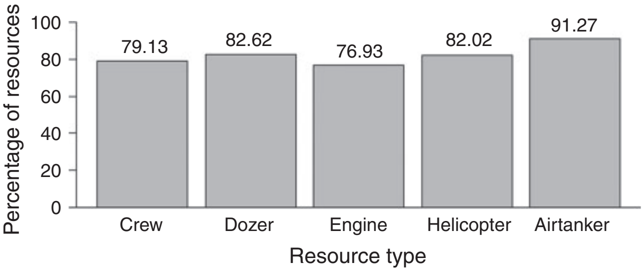

Fig. 5. Percentage of total resource assignments by individual resource type assigned during the containment phase.

much resource productive capacity is used on large fires than is theoretically necessary to contain a fire. We did not observe a significant difference by fire size, despite the complexity of the management problem varying greatly. However, we did observe increased effectiveness, as indicated by exposure index, on some of the smaller fires, suggesting there is room for improvement (Fig. 3).

We also want to make it clear that our analysis was based on retrospective calculation of daily and final perimeter; two values unknown at the time these daily reports are made. Our retrospective calculations do not consider the uncertainty faced by fire managers in this time-pressured environment. However, our results are consistent with the findings from other research applying production theory to wildfire management. Holmes and Calkin (2013) used operational data to estimate a Cobb–Douglas production function for fireline construction during large-fire management. Daily measurements of fireline production by resource type were calculated from the percentage of total fire containment reported by the acting IMT. Estimated production rates ranged from as low as 14% (engines) to 93% (helicopters) of those experimentally derived by Broyles (2011), with handcrews and bulldozers averaging ~35% and 18% (Broyles 2011; Holmes and Calkin 2013). Our findings suggest that using reported containment values from ICS-209 forms bias these estimates low because the reported values tend to underestimate actual containment. However, their estimates for handcrews are representative of the amount of time they typically spend constructing line on fires as observed on actual incidents that may be a result of inefficient resource management or use for alternative tasks other than fire line construction (Broyles 2011).

Recently, a stochastic frontier analysis was used to examine the production of controlled fireline during the suppression of large fires (Katuwal *et al.* 2016). This analysis allowed for the simultaneous assessment of control line (i.e. the portion of a daily fire perimeter that is part of the final fire perimeter), production efficiency of responding resources, and the factors that improved or reduced their efficiency. Their observations gave unexpected results that provide insights into, and implications for, the effectiveness of large-fire management. Handcrews were negatively correlated with the amount of final fire perimeter created on a given day, but bulldozers and fire engines contributed positively. Several operational factors may have contributed to the negative correlation between handcrews and control line production. First, firelines constructed by handcrews are inherently less secure because of their smaller width and reduced support from wildland fire engines constrained to road travel and the distance of their pumping capacity. Second, the length and location of breached and burned over handlines are not documented and therefore were not included in their analysis (Katuwal *et al.* 2016). This does raise significant questions regarding the tactical response and potential placement of firelines in locations with a low probability of success. Third, handcrews often conduct indirect burn out operations that may take several days to prepare before firing. Lastly, handcrews are often engaged in activities other than construction of fireline, such as point protection, contingency line construction or support for other resources; the lack of good documentation for these activities limits post-incident evaluation.

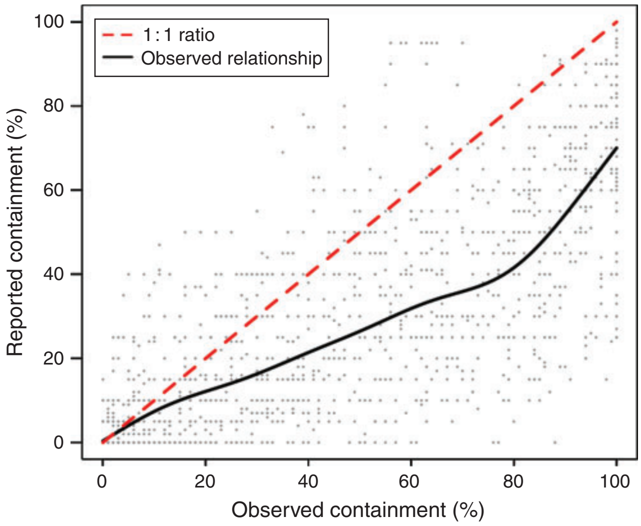

Fig. 6. The average relationship between observed containment and reported containment for large fires in the western US. Each point represents the reported value for an individual fire as related to observed final fire perimeter contained and the solid line represents the mean relationship.

Table 7. Percentage contained reported in ICS 209 when fires stop growing

Year	Number of fires	Percentage contained reported in ICS-209 when fires stop growing
2010	15	63.8
2011	22	70.27
2012	62	71.06
All	99	69.79

Table 6. Results from linear mixed-effects model comparing percentage containment of observed final fire perimeter and reported percentage containment on ICS-209 forms

AIC, Akaike's Information Criterion; BIC, Bayesian Information Criterion. logLik indicates the log-likelihood value

	AIC	BIC	logLik		
$n = 1482$	12 122	12 149	−6056		
Groups = 119					
Random effects:					
	Intercept	Residual			
s.d.	12.215	13.107			
Fixed effects:					
	Value	s.e.	d.f.	*t*-value	*P*-value
Intercept	28.13	1.2129	1362	23.192	<0.0001
actual.contain	41.149	4.5341	1362	9.0755	<0.0001
Parametric coefficients:					
	Estimate	s.e.	*t*-statistic	Pr(>|*t*|)	
Intercept	28.13	1.213	23.2	<0.0001	
Approximate significance of smooth terms:					
	Estimated d.f.	Ref. d.f.	*F*-statistic	Pr(>|*F*|)	
s(actual.contain)	6.162	6.162	613.5	<0.0001	
R^2(adj) = 0.606					
Scale estimate = 171.78					

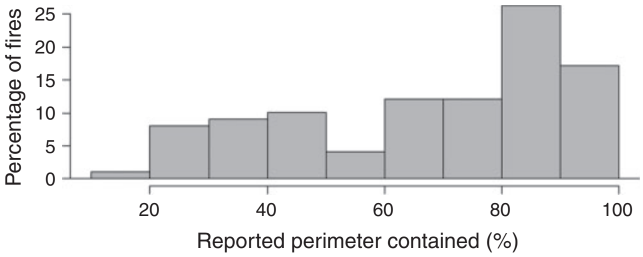

Fig. 7. Distribution of reported containment values and percentage of fires when we observed actual fire cessation on large fires in the western US.

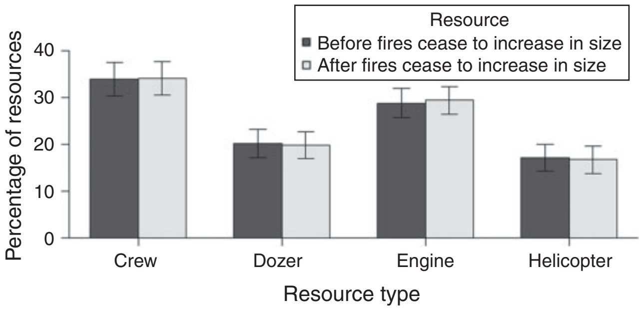

Fig. 8. Mean and 95% confidence intervals of the mean of the relative percentage of individual resource types as estimated by productive capacity during the containment and control phases of large-fire management. Resource packages appear similar in each phase, although absolute productive capacity was significantly different.

Aerial resources may not contribute significantly to line production (Katuwal *et al.* 2016). This effect is at least partially a result of their use during the height of the burning period when effectiveness is likely reduced (Stonesifer *et al.* 2016). Aerial resources may provide synergistic effects with ground resources during control line production, but these objectives and results are not readily documented and therefore are difficult to evaluate. Assuming aerial resources provide a tangible benefit to control line production without confirmation may have significant consequences because fatalities associated with their use have been as abundant, or more abundant, than those associated with other firefighting hazards (Butler *et al.* 2015). In addition, our analyses suggest that both helicopters and air tankers are retained after actual containment is achieved without good documentation on their benefits or need.

This study does not directly associate resource use to fire managers' attitude and risk perception. Our discussion is based on our resource allocation results and remarks from previous studies. Several factors influence the combination and allocation of resources employed during large fire management, including the operational environment (e.g. fire weather, topography, fuel conditions, presence of highly valued resources) and social, psychological and institutional factors also affect decision making (Calkin *et al.* 2013; Thompson 2014). In particular, fire managers' risk perceptions are important determinants of their decisions and have been shown to be correlated with fire management expenditures (Canton-Thompson *et al.* 2008). Accordingly, fire managers may have different preferences towards managing fires based on their personal experience and risk perception (Hand *et al.* 2017), such that resource combinations and use vary during the containment and control phases of an incident. Risk-aversion to potential re-ignition or escape following containment may result in excessive mop-up that unnecessarily exposes firefighters to hazards, increases incident management costs and consumes resources that could be more useful on higher-priority incidents. Additionally, as discussed by Holmes and Calkin (2013), there may be a tendency for fire managers to hoard resources for the low-probability they are needed on that incident, for IA of nearby ignitions, or future use within a particular geographic area when resource scarcity is perceived.

We observed a noteworthy amount of resources, including helicopters and air tankers, still assigned to the incidents after the containment phase of the fire. More than one fifth of the responding resources were committed to the fire after they stopped actively spreading. These results suggest a need to understand the appropriate amount of resource effort that balances the likelihood and consequences of a fire crossing containment lines against the opportunity cost of their use on other fires as well as responder exposure to fireline hazards. The difference in proportion of resource assignments observed during the control (*v.* containment) phase was greater on smaller and shorter duration fires, likely due to a lag in mop-up that begins along the heels and flanks shortly after the fire suppression effort began. On large, long-duration fires significant mop-up occurs on these areas while the fire continues to grow, with less opportunity for such mop-up efforts on smaller, short-duration fires. Alternatively, managers may be reluctant to release resources even if the probability of fire escape is fairly low due to perceived consequences of re-ignition (Canton-Thompson *et al.* 2008). These actions can unnecessarily increase responder exposure throughout the containment and control phases of large-fire management, which is evident in the variation in incident exposure index where more resources were clearly used than necessary to contain a fire at optimal efficiency (Fig. 3).

Economic inefficiency also occurs when the marginal benefit of resources assigned to existing incident precludes their involvement on fires where the marginal benefit may be higher. This potential becomes even more critical during periods of high fire loads where a delay in resource demobilization from stable and non-spreading fires compromises IA or the management of actively spreading fires. The observed volume of suppression resource assignments after cessation of fire growth may imply that fire managers do not sufficiently consider opportunity costs associated with alternative fire assignments relative to retaining resources on the current event. Essentially, the opportunity cost of these actions is zero when risk of damage from other fires is not considered. As indicated by some of the respondents surveyed by Canton-Thompson *et al.* (2008), fire managers choose the option that minimises personal loss rather than maximizing expected value of net gains, which is consistent with regret theory (Bell 1982). The potential negative after-effects of burning homes or other values at risk likely exceed those of using excessive suppression resources. Currently, it is not clear how significant the probability of rekindling and escape of fires is after they are contained, even though it may contribute significantly to inefficiencies in large-fire management. The extent to which resource scarcity has affected overall wildfire management is unclear and beyond the scope of this paper, but significant benefits may be derived from future research examining potential consequences.

We observed substantial differences between reported percentage contained and proportion of final perimeter established on a daily basis. We should note that fire cessation does not necessarily imply 100% containment; it only indicates that the fire did not spread after that specific day. Fire managers may not report a portion of the fire contained until the fire has line around it and they reach some level of confidence that the fire will not spread beyond a given portion of the line, which typically requires a few days of mop-up.

The discrepancies between reported and actual containment may be even greater than our analysis suggests as we derived actual containment estimates from final fire perimeter length. This perimeter length is greater than any other day during the containment phase. By definition we would expect the daily percentage contained reported in ICS-209 forms to be even higher, such that the difference in reported values would be less (or the relationship inverted) than represented in Fig. 6. In fact, our average estimates suggest reported values are more indicative of the percentage of a fire controlled. The National Wildfire Coordinating Group clearly defines a controlled fire as, 'the completion of control line around a fire, any spot fires therefrom, and any interior islands to be saved; burned out any unburned area adjacent to the fire side of the control lines; and cool down all hot spots that are immediate threats to the control line, until the lines can reasonably be expected to hold under the foreseeable conditions' (National Wildfire Coordinating Group 2017). Inaccurately reporting percentage contained could transfer risk to other incidents during periods of resource scarcity when allocation decisions become critical to enterprise-wide operational efficiency, safety and success. Adhering to the original and clear containment definition based on actual percentage of a fire perimeter with a completed control line could help prevent confusion and facilitate programmatic efficiency.

Fire management decisions are derived from risk-based heuristics prone to variation in an individual's perception of risk (Maguire and Albright 2005). Evidence suggests fire managers may be overly risk averse, often resulting in decisions that do not minimise expenditures, fire impacts or responder exposure (Wilson *et al.* 2011; Hand *et al.* 2015). Previous studies have suggested that fire managers may over-allocate resources even when the likelihood or potential damage from a fire is low (Wibbenmeyer *et al.* 2013). Suppression work does not necessarily stop when fires are no longer spreading: suppression resources continue extinguishing the fire until declared 100% contained or out. Several activities such as patrolling, line consolidation and blacking are necessary and must continue after fires cease to increase in size. Resources are required to fully contain, control and declare a fire out, but whether or not retaining 21% of resource capacity after fires stop spreading is efficient is not clear. Although weather and topographic conditions cannot be controlled or readily altered, many of the other factors that influence suppression resources and suppression costs are under the control of the IMT. Because many aspects of the use of responding resources and fire management costs are under control of fire managers, careful review could provide some opportunities to improve efficiency, reduce costs and responder exposure. We recommend investing in the necessary research to better identify where and when opportunities to improve effectiveness exist. These may include releasing resources when the likelihood of re-ignition, subsequent fire spread, and potential loss is sufficiently low relative to the direct and opportunity costs of their continued use. Investigation of regional assignment of resources, as well as variation among IMTs, will also provide some important insights towards the effective use of suppression resources.

Although fire managers may be interested in pursuing efficient response strategies (Canton-Thompson *et al.* 2008), they often choose more resource intensive strategies because of social and political constraints that incentivise response strategies inconsistent with cost-minimising objectives. Currently, fire managers have little incentive to consider cost because of lack of agency support and increased risk of personal liability (e.g. Canton-Thompson *et al.* 2008) in decision making, despite the fact that the federal policy dictates that cost of response efforts be commensurate with expected values protected (Fire Executive Council 2009). After reviewing several studies, Donovan and Brown (2005) concluded that the physical site characteristics do not fully explain the observed variations in fire management cost. The authors suggested that individual fire manager's preference and attitude are critical in understanding fire costs, so it is important to consider the attitudes of individual fire managers. Incentives lead to fire managers focusing on minimizing risk of damage without consideration of costs or the efficient use of resources (Canton-Thompson *et al.* 2008). For instance, choices among alternative response strategies were found to be driven largely by consideration of risk to homes and high-valued resources but were insensitive to increases in costs or responder exposure (Calkin *et al.* 2013).

The efficiency and effectiveness of suppression resources for large wildfire suppression is unclear due to the uncertain nature of fire management (Thompson and Calkin 2011). Tradeoffs between suppression resource cost, firefighter exposure to hazards and the range of values that may be protected by fire management activities are non-commensurate and difficult to assign monetary value (Venn and Calkin 2011). It has been debated (e.g. Donovan and Brown 2005) that costs and cost effectiveness of suppression effort have rarely been regarded as a priority and it is argued that many IMTs operate under the assumption that suppression resources are available to them without cost considerations.

ICS-209 reports contain a wealth of information on several aspects of large wildfire suppression and fire progression (Finney *et al.* 2009; Holmes and Calkin 2013; Thompson 2013). There are concerns about the errors and possible mischaracterisation of information such as cost and percentage contained (Gebert *et al.* 2007; Thompson *et al.* 2013). Because lack of reliable data further hampers analysis, there is a need for greater emphasis on collecting operational data that are reliable and accurate to study effectiveness and efficiency of large wildfire management. As suggested by Holmes and Calkin (2013), there is an advantage to using operational data to evaluate resource productivity, in that these data reflect the challenges faced by decision makers as they make actual day-to-day fire containment efforts. The application of economic theory and analyses can highlight opportunities to improve the efficiency of fire management response that can simultaneously reduce costs and minimise responder exposure, but improved data and further scientific examination is needed (Mendes 2010; Holmes and Calkin 2013; Katuwal *et al.* 2016). We believe investing in improved data acquisition and storage would allow for more analyses that can provide insights into resource and fire management efficiency and potential ways to improve the safety and effectiveness of wildland fire response.

Acknowledgements

We thank Jeff Kaiden, Jon Rieck and Amy Steinke for assistance with data. We also thank the three anonymous reviewers for their insightful reviews and comments on an earlier version of the article.

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