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Review

A review of challenges to determining and demonstrating efficiency of large fire management

Matthew P. Thompson[A,D], *Francisco Rodríguez y Silva*[B], *David E. Calkin*[C] *and Michael S. Hand*[C]

[A]US Department of Agriculture Forest Service, Rocky Mountain Research Station, 240 West Prospect Road, Fort Collins, CO 80526, USA.
[B]Department of Forest Engineering, Forest Fire Laboratory, University of Córdoba, Edificio Leonardo da Vinci, Campus de Rabanales, E-14071 Córdoba, Spain.
[C]US Department of Agriculture Forest Service, Rocky Mountain Research Station, 800 East Beckwith Avenue, Missoula, MT 59801, USA.
[D]Corresponding author. Email: mpthompson02@fs.fed.us

Abstract. Characterising the impacts of wildland fire and fire suppression is critical information for fire management decision-making. Here, we focus on decisions related to the rare larger and longer-duration fire events, where the scope and scale of decision-making can be far broader than initial response efforts, and where determining and demonstrating efficiency of strategies and actions can be particularly troublesome. We organise our review around key decision factors such as context, complexity, alternatives, consequences and uncertainty, and for illustration contrast fire management in Andalusia, Spain, and Montana, USA. Two of the largest knowledge gaps relate to quantifying fire impacts to ecosystem services, and modelling relationships between fire management activities and avoided damages. The relative magnitude of these and other concerns varies with the complexity of the socioecological context in which fire management decisions are made. To conclude our review, we examine topics for future research, including expanded use of the economics toolkit to better characterise the productivity and effectiveness of suppression actions, integration of ecosystem modelling with economic principles, and stronger adoption of risk and decision analysis within fire management decision-making.

Additional keywords: decision analysis, economics, risk, uncertainty.

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Introduction

Wildland fires affect human health and safety, communities, infrastructure, watersheds, soils, recreation and tourism, timber and non-timber products, cultural resources, biodiversity, and a host of other ecosystem services. The most acutely felt impact is loss of public and responder lives, highlighted by tragic events such as the 2007 Greece forest fires, the 2009 Australia Black Saturday bushfires and the 2013 Yarnell Hill Fire in Arizona, USA. Exposure to smoke and other air pollutants, exemplified by the extreme 2015 Indonesia fire season, can lead to further morbidity and mortality (Kochi *et al.* 2010; Johnston *et al.* 2012). Population growth, land-use change, expanded development of the wildland–urban interface, increased stress on ecosystems and lengthened fire seasons due to climate change all contribute to heightened global concerns over the impacts of fire (Molina *et al.* 2009, 2016; Stephens *et al.* 2013; Moritz *et al.* 2014; Calkin *et al.* 2015; Jolly *et al.* 2015; Abatzaglou and Williams 2016).

As concerns similarly escalate regarding how to best respond to wildland fires in resource-constrained policy and decision environments, there is increasing recognition that any proposed solutions to wildland fire problems must be inspired by decision analytic and economic principles (Martell 2015; Rodríguez y Silva and González-Cabán 2016). That is, given the complexity and uncertainty of fire response, decision-support systems are likely necessary to help fire managers determine and demonstrate effective and efficient solutions (Mavsar *et al.* 2013; Pacheco *et al.* 2015). Broadly speaking, by effective we mean yielding desirable fire outcomes, and by efficient, we mean doing so in a manner less costly than alternatives with equal effectiveness. A basic guideline for response efficiency in this context is to increase suppression effort up to the point where the marginal cost equals the marginal damage avoided (Headley 1916; Sparhawk 1925; Donovan and Rideout 2003).

Embedded within this condition for efficiency are a few important assumptions and prerequisites. First, that increasing suppression effort decreases net damage (losses less benefits), i.e. the partial derivative of net damages with respect to suppression is negative. Second, that avoided damages can be monetised to compare against suppression expenditures, i.e. cost–benefit analysis is possible. Third, that the outcomes of suppression actions in terms of avoided damages can be quantified, i.e. suppression resource productivity and effectiveness along with counterfactual scenarios can be credibly modelled. To clarify, this third condition states that quantification of avoided damages is reliant on some way to estimate what would have happened had other actions been taken. This generalised model for efficient incident management shares some key commonalities with the strategic budgetary planning model known as Cost plus Net Value Change (Sparhawk 1925; Donovan and Rideout 2003), although decision context, scope and scale are different.

In practice, limited information and other uncertainties often preclude direct applicability of such a cost–benefit model to inform real-time incident decision-making (Calkin *et al.* 2011; Thompson and Calkin 2011; Zimmerman 2012). Instead, minimising the sum of costs plus net damages might be better described as a guiding principle rather than a quantifiable objective. A critical additional variable that influences fire manager response is firefighter safety, wherein safety risks possibly increase with suppression effort (Donovan and Brown 2005). Thus, fire managers face difficult trade-offs surrounding resource impacts, suppression expenditures, firefighter safety and other factors (Calkin *et al.* 2013; Wibbenmeyer *et al.* 2013; Hand *et al.* 2015).

Here, we focus on questions of efficient management for those rare events that escape initial control efforts to become larger, longer-duration fires. We recognise that using size- or duration-based thresholds (e.g. 121 ha is often used in the United States) to identify what constitutes a 'large fire' is in some sense arbitrary (Calkin *et al.* 2014*a*), and as such, resolving a clear definition is not useful for our purposes. Instead, the motivating point to understand here is that there are different and perhaps broader challenges associated with this decision context relative to rapid initial control. We focus on these larger fire events because they are relatively more dynamic, complex and uncertain: decisions unfold over longer timeframes and broader spatial scales; a greater amount and diversity of suppression resources are used; a broader range of suppression strategies and tactics are implemented; and fire behaviour is inherently more resistant to control, resulting in lower probabilities of success (Finney *et al.* 2009; Thompson 2013). These rare large fire events often account for most of the annual area burned, pose significant safety concerns and result in high levels of suppression expenditures and damages (Calkin *et al.* 2005; Williams 2013; Short 2014). Further, existing studies on large fire management suggest possible inefficiencies in terms of suppression resource usage and expenditures (Calkin *et al.* 2013; Rodríguez y Silva and González-Cabán 2016; Stonesifer *et al.* 2016).

Although there exists a large body of research on efficient fire management, most efforts have focused on initial control efforts, whose principal objective is often to keep new ignitions contained as small or as quickly as possible (e.g. Fried and Fried 1996; Fried *et al.* 2006; Ntaimo *et al.* 2012). Modelling of initial containment typically compares the cumulative fire-line productive capacity of suppression resources against the growth rate of the fire (e.g. Fried and Fried 1996). As stated above, however, large fire containment efforts can be different undertakings with a limited empirical basis to characterise productive capacity and effectiveness (Finney *et al.* 2009; Thompson 2013; Calkin *et al.* 2014*a*; Fernandes *et al.* 2016; Katuwal *et al.* 2016).

In this paper, we review the decision environment and informational needs of incident managers as they develop and implement large fire management strategies. In particular, we target evaluation of alternatives and consequences as critical steps in the decision-making process. We describe key uncertainties as they relate to these steps, discuss existing decision-support approaches, and identify opportunities for fire economics and related research to fill in knowledge gaps. Throughout, for illustrative purposes, we draw comparisons between the authors' collective experience with fire economics and management in Andalusia, Spain, and Montana, USA.

This work is motivated in part by recent literature highlighting a lack of understanding within the fire management community of economic concepts, principles and tools (Clayton *et al.* 2014), limited incorporation of economic factors within fire management decision-support systems (Mavsar *et al.* 2013) and a large and growing gap between the decision-support needs of fire managers and the decision-support tools currently available (Martell 2011; Minas *et al.* 2012). We further draw from several review papers focused on related questions of fire impacts, resource valuation, optimisation, fire management operations, fire modelling, uncertainty and risk, and decision support (Bowman and Johnston 2014; Hand *et al.* 2014; Milne *et al.* 2014; Minas *et al.* 2012; Duff and Tolhurst 2015; Martell 2015; Omi 2015; Pacheco *et al.* 2015). We attempt to link insights from these strands of research to identify productive paths forward to improve the efficiency of large fire management.

Large fire management decision context

As stated above, decision-making on large fires is a dynamic and time-pressured process. Response strategies and tactics along with mobilisation and demobilisation of suppression resources change in response to evolving conditions and forecasts. Managers face choices regarding when and where to deploy different types, amounts and combinations of resources, and for what purpose. Specific missions (e.g. keep the fire south of the highway) and accompanying actions (e.g. direct attack with hand crews) must be coordinated with other missions as a set of means to achieve a desired end. These decisions can expand or constrain options in future burning periods, span areas ranging from dozens to tens of thousands of hectares, and unfold over time scales extending from hours to days to weeks.

In decision analytic terms, fire managers are effectively presented with a multistage stochastic optimisation problem, meaning that they face recurrent decisions aimed at best achieving objectives in response to uncertain and changing conditions. A well-defined set of uncertainties typically influence decision processes such as this, including the inherent variability of the natural world, the limited control of human interventions into natural systems, and knowledge gaps in how to model evolution of the system in response to environmental variation and human intervention (Williams 2011). In the fire management context, these uncertainties manifest themselves for example in terms of unpredictable fire weather, constructed fire-lines that are ineffective and burn over, and unknowns when jointly modelling fire spread and the moderating effects of suppression actions on fire spread (Finney *et al.* 2011*a*; Thompson 2013; Duff and Tolhurst 2015).

Table 1. Factors that influence the decision context

Factor	Issues and considerations
Values at risk	Population density, asset density, natural and cultural resources, social preferences, asset vulnerability
Fire regime	Cause (anthropogenic vs natural), size, duration, frequency, severity, departure
Disturbance interactions	Fire-on-fire interactions, invasive species, insect and disease, post-fire erosion and debris flows
Incident response capacity	Training, suppression resources, detection networks, budget
Land management	Timber and commodity production, fuel management, degree of current landscape modification relative to natural or historical patterns and processes
Fire management policy	Spectrum from fire exclusion to managed fire for resource benefits
Land-use change	Agricultural abandonment, ex-urban development
Land ownership	Government and private ownerships along with relevant objectives, policies and regulations
Organisational structure	The incentive system under which decisions are evaluated and managers are rewarded
Sociopolitical expectations	Influence of affected communities and governmental officials on fire manager decision space

Over longer time horizons, fire managers similarly face a multistage optimisation problem in terms of response to a series of fire events over multiple fire seasons. Insofar as the actions on a fire today can influence future hazard and risk, near-term decisions ought to include these possible impacts. That is, comprehensive evaluation of suppression strategies includes not only near- and long-term consequences of fire, but also near- and long-term consequences of fire suppression. In certain fire-prone ecosystems, the exclusion of fire can lead to reinforcing feedbacks where fuel loads accumulate, fires become more resistant to control, and there is greater demand for suppression (Calkin *et al.* 2015). These feedbacks can be complicated to unravel, but carry implications for future fire activity, fire consequences, suppression costs and landscape health (Houtman *et al.* 2013; North *et al.* 2015; Parks *et al.* 2015, 2016; Stephens *et al.* 2016).

A wide range of factors define the decision context (Table 1), and collectively, these factors can influence the scale of decision-making, the magnitude of uncertainty, how objectives are framed, and what response options are available. To illustrate variability in decision context, we compare a select set of factors from Andalusia, Spain, and Montana, USA. Although these areas share some commonalities, such as large areas of forested mountainous terrain, resource-dependent economies, popular protected areas (e.g. Doñana National Park, Glacier National Park) and increasing costs of fire suppression, there are many important differences. Specifically, we highlight differences in values-at-risk, fire regime and policy.

- Values-at-risk: the wildland–urban interface represents perhaps the starkest difference in values-at-risk between the two regions. Notably, although Montana is over four times the size of Andalusia, it has only one-eighth the population. The high population density in Andalusia coupled with intense urbanisation and the abandonment of rural lands and rural activities such as traditional forest management lead to increased complexity surrounding fire management in the wildland–urban interface. Homes in Spain are often constructed with fire-resistant materials so structure loss is not always a major concern, but limited egress and evacuation options in many densely populated areas lead to elevated public safety concerns.
- Fire regime: whereas in Andalusia most fires are human-caused and result in a human-dominated regime, in some areas of Montana, a more natural fire regime exists. Differences in fire regime that influence management strategies and actions relate primarily to the size and duration of large fires. In Andalusia, one of the largest forest fires in recent years occurred in 2004 in the province of Huelva, when the Minas de Rio Tinto Fire burned 29 867 ha over 27 July–4 August and tragically killed two people. More recently, in 2012, a fast-moving fire burned ~8250 ha in the Málaga province in just 12 h, causing over €30 million in damages and interrupting tourism activities in the popular Costa del Sol. By contrast, fires in Montana, even those with significant wildland–urban interface concerns, can be much larger and longer-duration events. The Jocko Lakes Fire in 2007 burned 14 726 ha near the popular resort town of Seeley Lake, destroying multiple structures, and took over 2 months to reach official containment. The Ash Creek Fire of 2012 burned over 100 000 ha from 25 June to 27 July. The dramatically longer fire durations in Montana can introduce greater uncertainty associated with forecasts of fire spread and suppression resource demands.
- Fire management policy: in Andalusia, fire exclusion is mandatory, such that potential ecological benefits of fire do not enter the decision calculus (it could be that benefits actually do equal zero) and full perimeter control to constrain fire size is a common response. By contrast, there is greater flexibility for response to unplanned fire on federal lands in Montana. In some cases, fires are managed for ecological benefits such that inhibiting fire spread is not a dominant concern. Hence, the more common use of actions like indirect attack, burnout operations and monitoring in Montana. Differing response objectives and strategies combined with vast expanses of contiguous wildlands managed for natural character (e.g. the 60 000-ha Bob Marshall Wilderness Complex) can partly explain the larger sizes and longer durations of fires in Montana.

Evaluating consequences and alternatives

An effective decision process relies on generating and evaluating the consequences of a range of available management alternatives (Hammond *et al.* 1999; Gregory and Keeney 2002; Gregory and Long 2009; Marcot *et al.* 2012), and many decision-support systems are set up at least in part to assist managers with these steps (Calkin *et al.* 2011; Noonan-Wright *et al.* 2011; Zimmerman 2012; Mitsopoulos *et al.* 2015; Pacheco *et al.* 2015; Kalabokidis *et al.* 2016). Imperfect information is the norm in fire response, meaning that fire managers often make decisions in the face of substantial uncertainty (Thompson 2013). Below, we discuss key uncertainties, organised around two principal pieces of information necessary to assess trade-offs across options and select a preferred alternative: the consequences of fire and the consequences of fire suppression.

Consequences of fire

Fire impacts are typically sorted into two categories: direct (e.g. human mortality and morbidity, destroyed homes and timber) and indirect (e.g. recreation, water quality). Direct losses are generally easier to quantify, for instance insured losses, although even these estimates may be misleading in cases where destroyed assets are uninsured or underinsured. Perhaps more problematic and more controversial is quantifying mortality and estimating the statistical value of a human life (Bellavance *et al.* 2009). Reisen *et al.* (2015) reviewed existing research on public health risk due to wildfire and concluded that significant knowledge gaps remain regarding how health effects vary with the duration and concentration of exposure to pollutants, and regarding the effects of exposure to chemical constituents beyond particulate matter. Jones *et al.* (2016) echoed these concerns along with highlighting health outcome data collection and methodological issues that challenge transfers of economic values and air quality concentration–response functions from the existing literature (see also Kochi *et al.* 2010, 2012).

The indirect impacts of fire can be substantial in magnitude and complicated to estimate as fires influence ecosystem processes beyond fire boundaries and over time (Venn and Calkin 2011; Stephenson *et al.* 2013; Milne *et al.* 2014). Wildfire incidents can affect water quality through increased sedimentation and erosion, and the supply of potable water from forested catchments (Smith *et al.* 2011). Fire effects to watersheds that supply municipal systems can result in costly remediation or infrastructure investments (Warziniack and Thompson 2013), but little is known about how values for water quality and supply are affected when degradation occurs outside high-value municipal watersheds.

In some cases, even the direction of fire consequences may be difficult to discern (Keane *et al.* 2008). As an example, the effects of wildfire on recreation values can be straightforward to quantify and have been illustrated in several contexts, but can be diverse and temporally non-linear (Englin *et al.* 2001). Recent wildfire increases the value for some types of recreation activities (e.g. hiking trips), but decreases the value for others (e.g. mountain biking) (Loomis *et al.* 2001; Hesseln *et al.* 2003, 2004). However, changes in values after recent fires attenuate over time as vegetation and sites recover from fire effects (Englin *et al.* 1996; Rausch *et al.* 2010).

Estimating net value change requires both a clear understanding of how fire impacts a broad range of natural and developed resources as well as the value society places on those resources. Roesch-McNally *et al.* (2016), among others, present methods for estimating the social value of forest ecosystem services, but how to translate results to a fire effects context is unclear. Hyde *et al.* (2013) documented limitations associated with effects of wildfire on natural resources, suggesting gaps in core sciences, limited technology transfer, and limited and frequently inconsistent spatial data sources. The authors summarised the challenges inherent in predicting ecological effect of wildfire due to complex spatial and temporal interactions within systems over time, concluding with a call for a consistent risk-based fire effects assessment framework. Venn and Calkin (2011) identified five primary challenges in estimating economic impacts of wildfire on natural resource values including a lack of scientific understanding on how non-market forest goods and services are affected by wildfire, difficulties in applying benefit transfer methods from other studies, few studies that estimated marginal willingness-to-pay to conserve non-market forest goods and services affected by fire, violation of consumer budget constraints and impediments to estimating indigenous cultural heritage values. Bowman and Johnston (2014) summarised the state of wildland fire (bushfire) economics as follows: 'Evaluation of direct and indirect economic costs of bushfire disasters, and bushfire management remains a poorly developed research frontier that demands collaboration of expertise from a broad cross-section of fields that often have limited experience of collaborating together'.

Questions of retrospective analyses of economic impacts notwithstanding, the more immediate informational need of fire managers is articulation of possible consequences from an ongoing fire event. Using existing retrospective studies as benchmarks and proactively assessing and mapping consequences (e.g. Castillo *et al.* 2017) provide useful first approximations. However, in this environment, aforementioned uncertainties surrounding fire effects valuation are compounded by unpredictable fire behaviour, which circles back to influence fire effects calculations given uncertainty over the intensity of fire to which resources and assets may be exposed.

Consequences of fire suppression

Fire suppression results in a broad spectrum of consequences, including resource impacts associated with suppression activities themselves, expenditures and firefighter safety. The former includes, for instance, soil degradation from construction of bulldozer lines, which can be at least partially rehabilitated post-hoc. Other impacts, however, may be less amenable to post-fire mitigation, such as aerial drops of chemical retardant falling into sensitive water bodies (Giménez *et al.* 2004). The costs of suppression are essentially a function of the amount and type of suppression resources used along with their respective assignment durations. Despite multiple studies of explanatory factors, there remains considerable uncertainty regarding the factors that drive wildfire management costs (e.g. Gebert *et al.* 2007; Liang *et al.* 2008; Donovan *et al.* 2011; Gebert and Black 2012; Yoder and Gebert 2012; Thompson *et al.* 2015*a*; Hand *et al.* 2016). Perhaps the greatest impact of engaging in fire suppression activities can be firefighter injury or fatality, resulting in continued attention on improving methods to evaluate factors like firefighter exposure, suppression difficulty and safety zones (e.g. Stonesifer *et al.* 2014; Campbell *et al.* 2016; O'Connor *et al.* 2016).

The main question, however, is how to develop reliable methods to estimate how consequences would change under alternative suppression strategies and tactics. In theory, any alternative would only be chosen if it was more efficient, which is premised on the existence of a framework for characterising efficiency. Production theoretic approaches have been proposed as a way to evaluate the efficiency of suppression operations, wherein suppression inputs (i.e. firefighting personnel and equipment) are combined to produce some output(s) of interest (Holmes and Calkin 2013; Katuwal *et al.* 2016). In other words, wildfire management can be viewed as a multi-output production process, with managers responsible for allocating inputs and balancing possible trade-offs across outputs.

Defining and observing the relevant output remains a major challenge. Length of containment line is an obvious first candidate (Mendes 2010), although additional factors like line width and location with respect to fire spread direction likely influence probability of success (Mees *et al.* 1993). Relevance of fire-line metrics dampen as suppression resources are used for activities other than containing or extinguishing fire (e.g. structure protection). Avoided area burned is a more informative metric (Mendes 2010), recognising that control lines do not necessarily always interact with the fire (i.e. indirect and contingency lines), and when they do, are not always successful (Thompson *et al.* 2016*a*). And yet this metric can be a poor proxy for actual consequences, especially where multiple types of objectives are important (e.g. expanding area burned for hazard reduction or ecological restoration).

A more useful, if at present aspirational, metric would look at avoided net damages attributable to a given strategy (Headley 1916). This requires some combination of expert judgement and modelling to compare alternative fire management scenarios on the basis of hypothetical consequences. Whereas model-based approaches are common to evaluate the consequences of fuel treatment strategies (e.g. Ager *et al.* 2013; Fried *et al.* 2016), models that evaluate alternative suppression approaches are rare. Perhaps the most relevant example is a modelling approach developed by Rodríguez y Silva and González-Cabán (2016). The authors derived a metric called the area contraction factor by simulating fire growth under the same burning conditions without any suppression operations, and then comparing simulated fire size with actual fire size. This approach that compares counterfactual simulated with actual fire outcomes is similar to other approaches used in the past (e.g. Cochrane *et al.* 2012), but here, the authors took the additional step of evaluating avoided damages to compare against suppression expenditures and evaluate efficiency.

Despite the utility of this approach as an evaluative tool to facilitate learning and improvement, as well as the utility of optimisation frameworks to explore the decision space (e.g. Petrovic and Carlson 2012; Belval *et al.* 2015, 2016), the reality is that prospective determination of plausibly efficient strategies remains elusive. That is, although the approach of Rodríguez y Silva and González-Cabán (2016) can determine the efficiency of past actions, it does not evaluate a range of other suppression strategies and tactics in terms of how they might be more or less efficient. Simply put, efforts to collect data on suppression productivity and effectiveness in operational large fire contexts and to develop research-quality reporting and information systems have not kept up with the capabilities of fire suppression modelling systems; hence, the limited ability to fully or even partially parameterise large fire optimisation models, and instead the continued reliance of many systems on assumptions, rulesets and expert judgment (Hirsch *et al.* 2004; Petrovic and Carlson 2012; Plucinski *et al.* 2012; Duff and Tolhurst 2015).

Although some data on production rates for individual suppression resources do exist (e.g. Broyles 2011), remaining knowledge gaps include productivity and effectiveness of different mixes of suppression resources, as well as how productivity and effectiveness vary with factors like timing, location, length of assignment and environmental conditions. Finney *et al.* (2009) identified periods of quiescent weather as significant variables determining containment probability, indicating that managers have only limited control on fire growth and are at least partially reliant on changes in weather to bring extreme events under control. Table 2 summarises a select set of studies that identify potential barriers to modelling suppression strategies and tactics directly (Wilson *et al.* 2011; Calkin *et al.* 2013; Holmes and Calkin 2013; Wibbenmeyer *et al.* 2013; Calkin *et al.* 2014*b*; Thompson 2014; Duff and Tolhurst 2015; Hand *et al.* 2015; Hand *et al.* 2016; Katuwal *et al.* 2016; Stonesifer *et al.* 2016; Thompson *et al.* 2016*a*). A key takeaway point is that there are different types of uncertainties at play, including variability in human behaviour, with implications for choices regarding model design and use (Riley and Thompson 2016).

Table 2. Barriers to directly modelling suppression efforts on large fires

Model consideration	Barrier
Suppression strategy	Incident managers exhibit variation in strategy selection and are often susceptible to sociopolitical pressures and decision biases
Resource use (amount, type and mix)	Incident management teams exhibit variation in resource use
Resource use (assignments)	Limited spatial data collected on activities such as fireline construction, aerial drops or burnout operations
Resource productivity	Fireline production rates in actual operational conditions can vary substantially from published estimates
Resource use and productivity	Limited understanding of resource substitutions, dependencies or synergies; nearly all models assume simple additivity of resource capacity
Suppression effectiveness (use)	Resources often used outside conditions where use is thought to be effective
Suppression effectiveness (monitoring)	Limited data collected on effectiveness of individual actions, collections of actions, or strategies

Table 3. Uncertainties faced in large fire management

Uncertainty	Issues and considerations
Fire consequence assessment	
Fire effects	Data availability and sufficiency issues, impacts to ecological processes over space and time, gaps in basic and applied fire science
Non-market valuation	Limited utility of benefit transfer due to contextual specificity of existing willingness-to-pay studies
Fire spread potential	Landscape conditions, weather conditions, modelled fire behaviour
Incident response and suppression consequence assessment	
Suppression expenditures	Sociopolitical pressures (e.g. community expectations, media coverage), managerial incentive structure, variability in decision-maker behaviour
Suppression resource productivity	Productivity of control efforts under different conditions and mixes of resources, intrinsic differences in crew capabilities and behaviours
Suppression resource effectiveness	Effectiveness of control efforts under different conditions and mixes of resources, probability of success, dispatch processes and resource arrival times
Counterfactual scenarios	How suppression efforts changed the fire behaviour and outcomes that might have otherwise occurred

Uncertainty assessment

Table 3 identifies and describes sources of uncertainty relevant to evaluation of consequences and alternatives, briefly summarising material discussed in the previous two subsections. The table first focuses on uncertainties relevant to impact assessment itself, and then on uncertainties relevant to how changes in suppression response might affect fire consequences. There is some overlap with Table 2, which we retain for completeness. More comprehensive uncertainty assessment could classify these uncertainties according to additional dimensions and evaluate their respective influences on model outputs and user confidence, an exercise left for future research (see also Riley and Thompson 2016).

Decision support approaches in Spain and the USA

In the past 10–15 years, research efforts that the authors have been involved with in Spain and the USA have attempted to make progress towards development of tools to facilitate improved quantification of fire impacts. Beginning with work from Spain, the SINAMI model (and later the *ECONOSINAMI* computer program) is based on marginal analysis techniques to get the point of greater budgetary efficiency, considering suppression costs, the net value change of resources and assets impacted by fire, and program management of wildland fire on a budget. The SINAMI model jointly simulates fire behaviour and suppression activities, requiring the user to enter as input the production rates of different suppression resources, their unit costs and the types of missions for which they are used. The model provides the functionality for users to explore the potential suppression costs and economic consequences of different combinations of suppression resources. The translatability of such a model to the fire management context in Montana, where a different range of suppression tactics like indirect line construction and intentional burnouts are employed, is unclear. Other recent fire economics models developed in Spain include the SEVEIF model (Molina *et al.* 2009) and the software *Visual-Seveif* (Rodríguez y Silva and González-Cabán 2010; Rodríguez y Silva *et al.* 2012). These tools can be used in real time to assess the losses associated with an ongoing or recently extinguished fire event, or for scenario analysis to assess potential losses from a given fire scenario that might occur in the landscape of interest.

Owing to some of the challenges identified above regarding complexity and uncertainty surrounding large, long-duration events, application of economic efficiency analysis to real-time incident assessment has not been as widespread in the USA as in Spain. Applied research has instead tended to focus on various components separately, such as potential fire impacts (e.g. Scott *et al.* 2012) or suppression expenditures (Hand *et al.* 2016). A major thread of large fire decision-support has focused on improved spatial risk assessment, for both incident response and pre-fire planning purposes (Calkin *et al.* 2011; Noonan-Wright *et al.* 2011; Thompson *et al.* 2016*c*). A key innovation here has been the use of stochastic wildfire simulation models to capture variation in ignition location and timing along with weather conditions to generate spatially explicit estimates of burn probability and fire intensity (Finney *et al.* 2011*b*). The risk-assessment framework is premised on quantifying expected and conditional net value change for resources and assets impacted by fire (Finney 2005), and has been applied on federal lands in Montana and elsewhere throughout the western US (Scott *et al.* 2013; Thompson *et al.* 2013*a;* Thompson *et al.* 2015*b*). In practice, risk metrics are quantified in effectively dimensionless units that are weighted by manager-determined relative importance weights rather than monetary terms, although the framework is sufficiently flexible to incorporate monetary value should decision-makers so desire.

Table 4 contrasts decision-support approaches used in Andalusia, Spain, and Montana, USA, for estimating fire effects in terms of net value change. Some of the most striking differences stem from differences in context, for instance deterministic versus probabilistic modelling and monetisation of net value change. The approaches also share key commonalities, for instance relying on expert judgment rather than separate specific models to quantify fire effects, in fact using very similar approaches (depreciation matrices and response functions) that estimate percentage loss or gain as a function of fire intensity. Use of specific fire effects models is possible (e.g. Tillery *et al.* 2014) but often requires translation of fire behaviour metrics, which can compound modelling uncertainty and create further difficulties in interpreting results. Neither approach at present

Table 4. Comparison of net value change estimation approaches used in existing decision-support tools

Attribute	Andalusia, Spain	Montana, USA
Context	Applied to specific fire scenarios, typically small fire and short duration	Applied to thousands of possible fire scenarios, typically large fire and long duration
Fire simulation approach	Deterministic	Probabilistic
Economic model	Cost–benefit analysis, net value change monetised	Cost-effectiveness analysis, net value change not monetised
Fire effects analysis	Expert judgement, depreciation matrix	Expert judgement, response function
Non-market valuation	Asset- and resource-specific equations from various peer-reviewed studies	Multicriteria decision analysis to assign relative importance weights to assets and resources
Key omissions	Limited inclusion of smoke impacts, responder safety and other health concerns; limited temporal horizons	Limited inclusion of smoke impacts, responder safety and other health concerns; limited temporal horizons

accounts very well for concerns surrounding responder and public safety, a key gap in many decision-support systems and the focus of ongoing research (e.g. Stonesifer *et al.* 2014). The tools also suffer from a limited ability to model the cumulative impact of fire management decisions and outcomes through time, for instance their influence on future fire activity and suppression expenditures (e.g. Houtman *et al.* 2013).

We should be clear that the two approaches outlined here do not represent the broad spectrum of existing and emerging risk analyses used around the globe. Differences in data collection and modelling methods notwithstanding, many of these efforts are converging on similar approaches to characterise the exposure of values-at-risk as well as the potential effects of fire (e.g. Chuvieco *et al.* 2014). In particular, use of stochastic wildfire simulation to model spatially explicit burn probabilities is increasingly common (e.g. Salis *et al.* 2013; Alcasena *et al.* 2015; Mitsopoulos *et al.* 2015; Mallinis *et al.* 2016; Oliveira *et al.* 2016).

Discussion

Large fire management decisions are ideally based on the evaluation of management options, their costs, safety implications, and how they may change fire outcomes. From this point of view, analyses that help quantify the effects of wildland fires on populations and the natural environment – a major thread of fire economics research to date – provide valuable but only partial information in the search for efficient solutions. That is, these types of studies tell us little about whether management actions or strategies played a role in the observed effects of wildland fires on people and the environment. Further, these types of studies provide little guidance for identifying how alternative large fire management strategies or courses of action might lead to reduced net costs and losses or to enhanced benefits. A better understanding of the relationships between wildfire effects, the provision of ecosystem services and the effectiveness of suppression efforts is necessary to assess trade-offs associated with response strategies.

Therefore, we argue, there is a need for a framework to evaluate the consequences of suppression to provide a reliable basis with which to evaluate alternative approaches to large fire management. Development of such a framework requires a credible ability to describe relationships between fire management activities and avoided losses. Beyond knowledge gaps associated with understanding suppression productivity and effectiveness, additional challenges to determination of efficient strategies include questions of how best to account for factors like probabilities, intertemporal feedbacks and trade-offs, and firefighter exposure. The relative magnitude of these and other concerns varies with the complexity of the socioecological context in which fire management decisions are made, as briefly illustrated for the cases of Andalusia and Montana. Despite the fact that fire policies in both locations imply an objective of economic efficiency within fire management operations, the incorporation of economics into strategic decision-making lags behind in practice.

We believe the lack of information and tools to facilitate more effective and efficient decision-making can acutely influence management of low-probability, high-consequence large fire events. Of the limited research that has been performed to date, several themes emerge that present challenges to efficient management: (1) large fire management can be qualitatively and significantly different from rapid initial response operations, and yet nearly all analyses targeting efficiency gains have focused on initial response; (2) suppression operations have only partial control over fire growth and can be overwhelmed by extreme weather; (3) fire managers can exhibit wide variation in how they respond to fires with similar characteristics; and (4) suppression resource use and effectiveness are poorly monitored. Recognising that incident management is really a linked sequence of decisions from initial response onwards, the ultimate aim here is not a better understanding of ‘large fire management’ alone, but rather a more comprehensive understanding of what courses of action are likely to best meet objectives from discovery through to control (and more broadly resource allocation decisions across fires and over time).

Although significant challenges exist, researchers and practitioners are making headway in improving the information and tools available to help inform efficient fire management solutions. We highlighted but two examples of many decision-support efforts developed to improve the efficiency of fire management around the globe. In that same spirit of supporting decisions and facilitating application of economics in strategic response decision-making, we offer potential avenues for future research efforts.

The first is to invest in empirically driven research to better characterise the productivity and effectiveness of suppression resources (Mendes 2010; Castillo and Rodríguez y Silva 2015*a*, 2015*b*; Duff and Tolhurst 2015). This necessitates acquisition of more and higher-quality data through monitoring efforts (e.g. Katuwal *et al.* 2016), as well as the establishment of frameworks with which to objectively evaluate effectiveness (e.g. Plucinski and Pastor 2013). This could include acquiring information regarding where and when suppression resources were used, under what conditions, and with what degree of success (Thompson *et al.* 2016*a*). Part of this research could explore new methods and functional forms for econometric models (e.g. Holmes and Calkin 2013), or could broaden the scope of analysis to consider, for instance, mixes of suppression resources. Improved monitoring data are a critical need for development of tools to evaluate multi-objective large fire response strategies.

Second, ecosystem modelling efforts could more strongly incorporate economic principles. Trade-off analysis is a core economic concept, and generation of efficient frontiers (e.g. Vogler *et al.* 2015; Ager *et al.* 2016) can help managers balance multiple objectives without being forced to reduce all aspects into monetary terms. Modelling approaches that link ecosystem models with management expenditure models could similarly help articulate trade-offs and move closer to cost–benefit analysis (Thompson and Anderson 2015).

Third, future research could more strongly incorporate principles from risk and decision analysis (Yoe 2011; Thompson *et al.* 2013*b*; Calkin *et al.* 2014*b*; Thompson *et al.* 2015*c*). This could entail more comprehensively identifying sources of uncertainty and their impacts on model outputs, and reframing decisions in probabilistic terms to consider factors like probability of success. Embracing risk management also means investing in pre-fire assessment and planning in advance of the problem to dampen time-pressures of incident response (Thompson *et al.* 2016*b*). These analyses can for instance consider factors such as resource susceptibility to fire, suppression difficulty and probable control points (e.g. Rodríguez y Silva *et al.* 2014; Thompson *et al.* 2016*c*).

Last, there exist significant opportunities to improve and expand the knowledge exchange across the global fire community. Although developing generalisable solutions and tools is difficult given heterogeneous contexts, we see great opportunity for fire management researchers to collaborate on topics related to resource allocation efficiency, strategic pre-fire planning and econometric analysis. There already exists a strong precedent for such collaboration through international workshops, seminars and conferences (e.g. International Symposium on Fire Economics, Planning and Policy; González-Cabán 2013). Last, in addition to the research community, these efforts could extend to educating the next generation of fire managers (e.g. http://www.masterfuegoforestal.es/, http://www.nafri.gov/, accessed 23 March 2017).

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