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A framework for developing safe and effective large-fire response in a new fire management paradigm

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ABSTRACT

The impacts of wildfires have increased in recent decades because of historical forest and fire management, a rapidly changing climate, and an increasingly populated wildland urban interface. This increasingly complex fire environment highlights the importance of developing robust tools to support risk-informed decision making. While tools have been developed to aid fire management, few have focused on large-fire management and those that have typically simplified the decision environment such that they are not operationally relevant. Additionally, fire managers need to be able to evaluate alternative response strategies that lead to tradeoff analyses balancing fire impacts, responder exposure, financial and resource investments, and probability of success. In this review, we describe limitations in existing operational research models from the perspective of large fire management decisions. We identify a broader set of objectives, decisions and constraints to be integrated into the next generation operational research models. Including these changes would support evaluation of a suite of response options and the efficient resource packages necessary to achieve response objectives, aiding decision maker's ability to minimize responder exposure while reducing the social, ecological and economic impacts of wildfires. We follow with a proposed framework for expanding current large fire decision support systems, and conclude by briefly highlighting critical research needs and organizational changes necessary to create and implement these tools and overcome the negative consequences of positive feedbacks derived from historical and current wildfire management policies and strategies.

1. Introduction

The social, ecological and economic impacts of wildfires have increased in recent decades because of the unanticipated consequences of historical forest and fire management, a rapidly changing climate, and an increasingly populated wildland urban interface (Hessburg et al., 2007; Naficy et al., 2010; Haas et al., 2013; Stephens et al., 2014; Jolly et al., 2015). Aggressive fire suppression and hazardous fuels reduction have been the two dominant management strategies employed in the United States to minimize contemporary fire effects. The interagency fire management community remains effective at suppressing 95–98% of fires during initial attack (IA), such that a small proportion of ignitions result in ~95% of annual fire extent (Strauss et al., 1989; Calkin et al., 2005; Short, 2014, 2015). These relatively few fires drive the observed trends of increasing annual fire extent and effects as they burn with greater intensity than those more easily suppressed (Finney et al., 2009; Littell et al., 2009; Reilly et al., 2017). The negative consequences derived from these fires also disproportionately influence fire response by reinforcing the perspective that aggressive suppression is necessary to minimize their negative impacts. This reaction only perpetuates the problem because fire exclusion leads to positive feedbacks in hazardous fuels, forest density, and societal expectations from the fire management system; a problem commonly referred to as the wildfire paradox (Arno and Brown, 1991; Calkin et al., 2015).

Hazardous fuels reduction treatments can reduce local fire effects and the probability of fire impacting highly-valued resources and assets (HVRA) (Raymond and Peterson, 2005; Ager et al., 2010, 2013; Kalies and Kent, 2016), but have not been implemented at a scale necessary to significantly alter large fire trends and effects because of various social, ecological and political constraints (Roloff et al., 2005; North et al., 2015). In contrast, annual fire extent is increasing and research has demonstrated that fire boundaries can be quite effective at inhibiting subsequent fire spread and improving response efficiency (Collins et al., 2009; Parks et al., 2013; Thompson et al., 2016b). Therefore, deemphasizing aggressive fire suppression in favor of variable response strategies that promote more fire on the landscape may be a critical component to any strategy attempting to minimize losses to contemporary wildfires and overcome the wildfire paradox (North et al.,

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2012). Implementing a variable response strategy across landscapes would support a transition of the fire management system to the new ecological fire management paradigm that deemphasizes aggressive fire suppression in favor of variable response strategies and tactics to meet resource objectives (Ingalsbee, 2017).

There is increasing recognition that a cultural shift in the fire management community is necessary to move towards this new fire management paradigm (Thompson et al., 2015). U.S. fire management policies currently provide managers the flexibility needed to pursue alternative wildfire response strategies, and have for some time, with little observable effect. New policy directions appear to acknowledge a need for additional change, as indicated by the three goals of the U.S. National Cohesive Wildland Fire Management Strategy: (1) fire-adapted communities, (2) resilient ecosystems, and (3) safe and effective response. We contend that fire managers are the only agents that have a direct influence on all three goals, but the structure of this system, including associated incentives and performance metrics, have developed systemic biases that hinder any significant change and benefits from flexibility in policies (Collins et al., 2013; Thompson et al., 2015; Thompson et al., in press). Agency administrators and fire managers are generally risk averse (Hand et al., 2015), and the dramatically changed fire environment as well as uncertainty regarding potential fire behavior and effects creates an increasingly complex decision environment (Thompson and Calkin, 2011). These factors promote a response bias toward status quo aggressive fire suppression as managers rely on default strategies when making reactive, time-pressured decisions (Canton-Thompson et al., 2008; Wilson et al., 2011; Calkin et al., 2013; Thompson, 2014). One potential path forward for overcoming these constraints is the adoption of enterprise risk management, where all agency decisions are grounded in sound risk management principles before, during and after decisions are made (Thompson et al., 2016c; Dunn et al., 2017).

Expanding or developing tools that support risk-informed decision making for large fires are key avenues for further infusing risk management principles into the fire management community and their supporting agencies. These tools can help minimize biases and manage or reduce uncertainty so that the flexibility afforded by current policies can be leveraged to reduce long-term risk. In particular, operational research (OR) models are advanced decision support tools that could expand the capabilities of a large-fire decision support systems. OR models include but are not limited to optimization models using mixed-integer or chance-constrained programming, task scheduling, and Markov-chain modeling. Several recent reviews have described the development and mathematical formulations of a multitude of tools used to model various aspects of wildfire management (Mendes, 2010; Minas et al., 2012; Duff and Tolhurst, 2015; Martell, 2015). Despite the increasing need there has been little research and investment into developing OR models for the large fire management problem (Duff and Tolhurst, 2015). Instead, the vast majority focus on fire prevention and initial attack (IA), possibly due to existing performance measures for fire management organizations that emphasize IA success rates and the misconception that all large fires are preventable. Therefore, these models are not operationally relevant or easily adaptable to large fire management because the problem formulation is not tiered to land and resource management plan objectives, available decisions and operationally relevant constraints are limited in scope, suppression actions are either not feasible or ineffective, and the dynamic and uncertain nature of managing these events over time is routinely ignored. However, they do provide valuable methodologies necessary to construct a more complex dynamic, multi-response model that would advance large-fire management decisions.

In this paper, we review existing OR models through the lens of large fire management, focusing on decisions that are made for managing incidents lasting more than three days and burning > 120 ha before containment. In many cases, these incidents exceed 10,000 ha, require management for weeks to months, and can cost tens to hundreds of millions of dollars to manage. We organize the paper in concert with the necessary formulations of OR models including the objective function, decision variables and influences on fire management decisions. We refer to these influences as constraints, consistent with OR model formulations, to represent factors that circumscribe the models decision and optimization environment. We do not necessarily conform to all aspects of how decisions are currently made on large fires because it is our belief they do not represent the best risk-informed decisions possible. We follow by proposing a framework for an expanded decision support system with the potential to overcome many of the identified limitations, and conclude by highlighting critical research needs that would reduce knowledge gaps and advance the capabilities of large-fire management decision support systems.

2. Objective function

Objectives define the desired result achieved through management actions and form the basis for response planning, strategy development, and tactical activities. These objectives must then be translated into an objective function that drives the solutions within an OR model. Two types of objectives are directly relevant to contemporary large fire management (Marcot et al., 2012). Ends-based objectives define the desired outcome from wildfires within the context of land and resource management plans (LRMP). These objectives aid in problem formulation, which is the first step in a risk-informed decision process for large fire management (Zimmerman, 2012). Formulating the problem correctly is important because there are two large fire occurrence-pathways that could have varying response strategies: (1) a decision to manage an ignition for resource objectives or, (2) a fire that escapes initial or extended attack capabilities typically due to severe fire weather conditions (Finney et al., 2009; Riley et al., 2013; Fernandes et al., 2016). This is further complicated by the fact that current U.S. fire management policies allow for a varied response on an individual incident that incorporates aspects of aggressive suppression and management for resource benefits. These pathways vary in their potential near and long-term fire behavior and effects, and therefore influence how a decision maker develops the response strategy. An OR model must be flexible enough to capture these distinct management problems to be relevant to contemporary large fire management.

Defining means-based objectives is arguably the most pressing and potentially important need for large-fire response, and these objectives would benefit from being specific, measureable, achievable, realistic and time-constrained (S.M.A.R.T.) (Doran, 1981). These may include multiple objectives such as protection of HVRAs, prevention of fire spread beyond spatially defined boundaries, minimized responder exposure to hazards, or the desired containment and control date. The tactical response is then based on achieving these stated objectives. Determining the suite of means-based objectives that should be captured by a large fire management OR model is currently hindered by a lack of well-defined objectives in practice, as indicated by a recent internal review of 2014 incident objectives that revealed that the majority do not meet the S.M.A.R.T. criteria (Wildland Fire Management Research, Development and Application, 2015). The lack of well-defined objectives also limits opportunities to develop an efficient response and forecloses opportunities to evaluate the effectiveness of chosen response strategies and tactics, a fundamental process for accumulating knowledge and improving risk-informed decisions.

Problem formulation is a major limitation in wildfire OR models because they default to employing an IA response strategy (aggressive, direct attack) even for large-fire management (Wei et al., 2011; Belval et al., 2015). Minimizing cost plus net value change (C + NVC) provides the theoretical framework and objective function for these models because it is perceived to have the flexibility to optimize resource acquisition and allocation for the fire management problem (Donovan and Rideout, 2003). However, minimizing C + NVC focuses exclusively on aggressive suppression and therefore does not account for the potential to manage wildfires for resource objectives; a strategy that can increase C + NVC for any individual incident but greatly reduce long-term expenditures and risk (North et al., 2012; Houtman et al., 2013; Collins et al., 2009). C + NVC also fails to account for other important aspects of the large fire decision environment, including but not limited to responder exposure, the challenges of appropriately quantifying non-market resource values (Venn and Calkin, 2011; Calkin et al., 2011a), and the ability to consider future benefits associated with fuels reduction from large fire occurrence. In addition, an optimized solution on C + NVC does not acknowledge the inherent uncertainty in both available information and the fire environment, and narrows the objective to costs and fire effects when in practice decision makers must balance responder safety and effectiveness with social and ecological resilience.

An alternative formulation of objective functions in OR models, not pursued to date but more representative of large fire management decisions, is the generation of efficient frontiers. An efficient frontier is a graphical depiction representing the boundary (maximum of factor Y given factor X) of a suite of large fire response options, and is adapted from portfolio theory (Markowitz, 1952). Fire managers can compare two factors, such as responder exposure to hazards and net value change, for each response option in relation to the efficient frontier boundary and choose a desired response strategy accordingly. The model would generate efficient frontiers for several metrics, allowing the decision maker to evaluate spatially explicit risk tradeoffs that balance multiple aspects of the large-fire decision environment. The assessed response options should be based on ends-based objectives, subject to available control lines, protection of HVRAs, among other factors (Moghaddas and Craggs, 2007; Katuwal et al., 2016; Thompson et al., 2016a; O'Connor et al., 2017). The efficient frontiers could then evaluate the expected social, ecological and economic impacts of the fire (eNVC), responder exposure (exposure index), financial and resource investments (costs, workload), and probability of success. We summarize these objective functions in Table 1 for quick reference and describe them further below. Each objective function represents a dominant consideration by fire managers, typically determined through a deliberative process. A management relevant OR model should quantify these factors to more accurately represent the complexity of the management problem.

The expected NVC would be a function of HVRA exposure to expected fire behavior as predicted following ignition or from pre-incident spatial fire risk assessments (Scott et al., 2013). Exposure index can be estimated as a function of the cumulative resource time invested in tasks with varying levels of hazard ratings such as direct line construction, indirect attack and burnout operations, point protection or aerial retardant delivery (Calkin et al., 2011a; Stonesifer et al., 2014). Investments would be estimated by forecasting the Stratified Cost Index (Hand et al., 2014) or abundance of various resources committed and unavailable to respond to other incidents. The probability of success could be estimated from fire behavior simulations that include variability in modeled fire spread and intensity, the likelihood of a line holding under these conditions, and chance-constraints that capture uncertainty in resource acquisition and allocation. The OR model would produce contrasts (i.e., efficient frontiers) of each objective for the various response options, supporting trade-off analyses for these major objectives. Evaluating these factors, rather than focusing on a single optimized solution, would be more representative of the large fire decision environment.

3. Decision variables

A series of linked decisions are necessary for safe and effective resource use on large fires. We summarize the decision variables that should be included in an OR model that captures the breadth of decisions made on large fires in Table 2, including examples of their use in OR models even though they are often used in isolation of other desired factors. We separate these decisions into two classes: (1) tactical response decisions that summarize the abundance of major tasks requiring resources, and (2) decision modules that determine the abundance, acquisition, allocation and demobilization of resources. These linked decisions vary across the response options evaluated in the tradeoff analysis, because several decision variables are derived explicitly from a given response option. This is particularly evident when considering the tactical response decisions. For example, a unique set of control lines, expected impacts to HVRAs and logistical features are specific to each option unless the decision maker is only evaluating the effects of changing the desired control date within an already defined containment boundary. The desired control date is included as a decision variable for instances when fires are managed for resource benefit and agency administrators expect fire containment before a season ending rain event, an accelerated control date is desirable because of a forecasted severe fire weather event, smoke management concerns, or national-scale resource scarcity warrants a more rapid conclusion to an incident.

In conjunction with expected fire behavior and effects, the factors identified as tactical response decisions shape the amount and timing of the tasks to be completed over the course of a fire event that may last weeks to months. We identify four dominant decision modules that support the efficient acquisition, allocation, and demobilization of responding resources (Table 2). The abundance of various resources depends on need, their effectiveness at completing identified tasks, and their availability (described later as a constraint). The resource abundance module captures these dynamics, as influenced by the relevant constraints. The resource acquisition module then determines the timing of resource orders, which depends on the order of operations for various tasks and their estimated start time. Upon acquisition, the resource allocation module then determines which resources are assigned to each task, also dependent on the relevant constraints for each task and resource. The resource demobilization module tracks the completion of tasks, availability of the resources for subsequent assignment, and the timing of their demobilization. These modules are indicative of large fire management decisions and necessary for efficiently managing responding resources.

Table 1
Risk trade-off objective functions to create efficient frontiers of various response options.

Objective	Definition	Examples of use
Responder exposure index	Summation of resource time engaged in tactical response tasks scaled by their relative hazard index and the environmental hazard index	none
Cost or workload	Costs or total quantity of resource commitment for entire response implementation. Both are relevant metrics as they can illicit different aspects of the response strategy and have different consequences for regional or national-scale fire management concerns	All models capture a portion of the costs, but not necessarily workload
Net value change (NVC)	Summation of positive and negative impacts to resources identified during spatial fire planning and integrated into LRMPs; should include assessment of non-market resources	All models have quantified NVC directly or through surrogates at least for market-valued resources
Probability of success	Likelihood of achieving strategic objectives given uncertainty in fire dynamics, resource production, resource availability and control line or point protection success. Control line and point protection success should be weighted based on consequences of failure for individual components	Mees and Strauss (1992) for line holding probability, not full strategy probability of success

Table 2
Important decision variables to include in a large-fire operational research model.

Tactical response decisions	Sub-categories	Description	Use
Control line construction (includes mop-up to control standards)	Location	– Spatially explicit location derived from pre-incident planning or *in situ* analyses of options	Not constrained to explicit locations in models
	Length by type	– Roads (existing travel or logging road infrastructure)	
		– Handlines (1 m of bare mineral soil with adjacent vegetation control)	Belval et al., 2015; Fried and Fried (1996); HomChaudhuri et al. (2010); Hu and Ntaimo (2009); Wei et al. (2011, 2015)
		– Dozer lines (bulldozer constructed control line)	Arrubla et al. (2014); Hu and Ntaimo (2009); Ntaimo et al. (2012, 2013)
		– Wet lines (use of water only to extinguish boundary and raise fuel moisture to its moisture of extinction).	None
		– Natural barriers (unburnable landscape features such as rivers, rock outcroppings, glaciers, etc.)	None
Point protection		– Highly-valued resources and assets requiring special protection and therefore the allocation of specific resources	van der Merwe et al. (2014)
Logistical-feature creation		– Operational features that support tactical response and require resource allocation to construct; Includes cleared areas used for logistical support (drop zones), crew and supply transport (helispots, parking), or operational resource safety (deployment or safety zones)	None
Containment or control date		– Should be flexible so it can be set by IMT based on programmatic needs, or determined by the optimization algorithm as the most efficient means to achieve desired objectives. Allows for variability in tactical response and evaluation of multiple scenarios and is necessary for quantifying resource needs	Mees and Strauss (1992)
Decision modules	**Sub-categories**	**Description**	**Uses**
Resource abundance		– Number of resource by type needed to achieve tactical objectives throughout the incident	
	Handcrews by type (Type I, II IA, II, III)	– Handcrews are diverse teams of career and temporary firefighters deployed as teams of 18–20 individuals with varying skills. They have decreasing skills set and physical aptitude with increasing number designator	Wei et al. (2011, 2015, 2017)
	Dozers by type	– D-6, 7 or 8	Ntaimo et al. (2012, 2013)
	Engines by type (Type III–VI)	– Crew size and water delivery specifications vary by wildland fire engine type, with Types III–VI and crew sizes of 3 to 5 firefighters commonly used in large fire management	van der Merwe et al. (2014); Wei et al. (2011, 2015, 2017)
	Water tenders	– Payload capacity and vehicle age	Wei et al. (2011, 2015)
	Helicopters by type (Type I–III)	– Size and payload capacity decline with increasing designator	Mees and Stauss (1992)
	Fixed-wing aircraft by type	– Airtankers varying by payload capacity	none
	Overhead personnel	– Based on ICS system requirements and span of control	none
	Support staff	– Logistical (e.g. camp crews, supply cache, catering), medical support, etc.	none
	Other mechanized equipment	– Excavators, road graders, etc.	none
	Professional tree fallers	– Capable of felling large or dangerous trees and snags (limited to certain vegetation types)	none
Resource acquisition		– Time during incident when resource should be acquired to account for changing fire conditions and resource assignment length	Rachaniotis and Pappis (2006); Kali (2016); Wei et al. (2017)
Resource allocation	Strike Team/Task Force	– Should an individual resource be allocated to a team to achieve tactical assignment?	Hu and Ntaimo (2009)
	Control line construction	– Handline	Belval et al. (2015); Donovan and Rideout (2003); Fried and Fried (1996); HomChaudhuri et al. (2010); Hu and Ntaimo (2009); Mees and Strauss (1992); Wei et al. (2011, 2015, 2017)
		– Dozer line	Arrubla et al. (2014); Donovan and Rideout, 2003; Hu and Ntaimo (2009); Ntaimo et al. (2012, 2013)
		– Roadside brushing and burnout preparation	none
		– Wet line	none
	Burnout operations	– Lighting crew – typically Type I handcrews	Not explicitly, but Fried and Fried (1996) considered indirect attack
		– Holding crew – any crew type	none
		– Securing crew – any, but typically Type II handcrews	none
	Point protection	– HVRA protection typically by engine or handcrew	van der Merwe et al. (2014)
	Drop, deployment or safety	– May require handcrews and mechanized equipment.	none

(continued on next page)

Table 2 *(continued)*

Tactical response decisions	Sub-categories	Description	Use
	zones and helispot construction	Often utilize old timber harvesting landings that need to be cleared of debris and improved for use	
	Contingency line construction	– May not be necessary with well-organized management effort, but some HVRAs may warrant their utilization	
	Mop-up	– Roads – can use engines and handcrews	none
		– Handlines – handcrews, but can obtain water support from engines	Hu and Ntaimo (2009) as holding resources
		– Dozer lines – handcrews, engines with 4 × 4 capabilities	none
		– Wet lines – for engines only	none
		– Natural barriers – handcrews, but can obtain water support from engines	none
	Patrol	– Monitoring of fireline after mop-up to ensure line remains intact	none
		– Concludes when perimeter has met mop-up standards and fire has been transferred to the local unit managers	none
	Rehabilitation following control (directly related to tactical response operations)	– Roads – road graders and excavators for damaged culverts in roads	none
		– Dozer lines – bulldozers to pull back berms; water bars and brush dispersion on line for erosion control	none
		– Handlines – handcrews; water bars and brush dispersion on line for erosion control	none
	Aerial control-line support (fixed-wing or helicopter)	– Reinforcement (retardant)	Mees and Stauss (1992)
		– Intensity reduction (water drop)	none
	Aerial crew transport, supply delivery	– Helicopter(s) needed to transport crews or deliver supplies to remote locations	none
	Hazard tree felling	– Limited to professional tree fallers (Type I crews capable within their tactical assignment area)	none
	Dust abatement	– Water tenders used on travel routes, helibases and fire camp for health and safety of fire management personnel	none
Demobilization		– As tasks are completed resources may be released for reassignment or rest	Rachaniotis and Pappis (2006); Kali (2016); Wei et al. (2017) on daily basis back to home unit
		– Must forecast future incident needs, benefits from adding a given resource to another task temporarily at lower efficiency versus acquiring a replacement for a future task, resource quality and number of days remaining for assignment	none

Existing OR models have not captured this complexity, instead focusing decisions on pre-positioning of scarce resources, or their optimal allocation across a defined landscape to achieve suppression objectives (Fried and Fried, 1996; Haight and Fried, 2007; Martell, 2007; Wei et al., 2015). Most have been developed to optimize IA by pre-positioning resources to minimize arrival times under the assumption it reduces large-fire occurrence (Lee et al., 2012). They have also optimized scarce resources across multiple fires under various scenarios to minimize damage to highly valued resources and assets (Petrovic and Carlson, 2012). Control line production is the primary resource task and models assume additive effects of additional resources. Most exclude special protection (point protection) of HVRAs (but see van der Merwe et al. (2014)), as well as activities associated with indirect attack (Table 2). All models have ignored demobilization decisions despite resource assignment lengths often being shorter than total fire duration, and the need to release resources not needed to perform tactical assignments effectively when cost is a management consideration. Instead, they rely on the completion of sufficient control line to surround the wildfire to conclude the optimization procedure, forgoing activities commonly used to control a wildfire such as mop-up.

The series of linked decisions necessary on large fire management regarding responding resources suggests the large fire management optimization problem is essentially a task-scheduling problem designed to use scarce resources optimally. This provides a theoretical basis, recently applied to basic wildfire scenarios, that could be expanded to more complex large-fire management situations (Rachaniotis and Pappis, 2006; Kali, 2016). Task-scheduling requires tracking the number of working days left on incident assignment for each resource (currently limited to 14 days), as well as forecasting resource needs. Optimizing this process ensures fire managers minimize resource order and retention to those necessary given the response option, as well as their optimal time of acquisition. Acquisition timing is important because many tasks build on the completion of others, depending largely on operational standards, order of operations and fire arrival time. Allocation follows acquisition depending on the schedule of tasks, requiring a large fire management OR model to forecast anticipated beginning and end date for each task, as well as the specific resource(s) assigned to accomplish it. Demobilization commences as fireline tasks are completed and enough resources remain to achieve current and near-term tactical objectives. These linked decisions are currently made on all large fires, but optimizing them could increase the efficiency of the tactical response and reduce resource exposure to unnecessary hazards. This could also prevent resource hoarding, an action where resources are retained beyond their optimal use period to be available in the event of an unexpected fire escape or ignition, when their use on other incidents might be more effective or efficient at meeting regional or national-scale objectives.

4. Constraints

Large-fire management decisions can be constrained by environmental conditions, resource limitations, and operational standards or conventions. We have summarized specific constraints relevant to large fire management into these three classes, and provided references for OR models that have explicitly captured each constraint. Many environmental factors (constraints) influence decision makers for large

Table 3
Environmental influences on decision variables.

Constraint (influence)	Description	Examples of use
Fire weather	– Long-term forecasts are needed for simulations of fire behavior to support strategic and tactical decisions	Static in all models that explicitly predict fire behavior as noted below
	– Hourly forecasts are necessary to constrain burnout opportunities and timing; can be used to identify trigger points for disengagement during burning period as well	none
Fuels and vegetation	– Fuel models and vegetation structure are necessary for fire behavior simulations; influences production rates of resources for various tasks	Dynamic in models with spatially explicit fire behavior predictions (e.g. Belval et al., 2015; Wei et al. (2011))
Topography	– Influence of slope, aspect, box canyons, saddles, ridges, and natural barriers on fire behavior at local and landscape-scales	Only varies in HomChaudhuri et al. (2010)
Fire behavior	– Fireline intensity and flame length, which influence resources that can engage with the fire and the probability of control line being successful	Belval et al., 2015; Mees and Strauss (1992); Wei et al. (2011)
	– Distance of daily fire spread across highly variegated landscapes	Belval et al., 2015; HomChaudhuri et al. (2010); Wei et al. (2011, 2015)
	– Estimated transition to crown fire that exceeds any potential control by operational resources	none
	– Growing perimeter length with suppression influence on boundary	Belval et al., 2015; HomChaudhuri et al. (2010); Hu and Ntaimo (2009); Wei et al. (2011, 2015)
	– The progression and intensity of the flaming front contributed by burnout operations should be incorporated into fire behavior simulations	none
Burnout fire behavior	– Often done well in advance of the firefront and therefore should be incorporated into simulations of fire behavior and the location of the daily fire perimeter to ensure do not compromise the tactical response	none
	– Fire must be of sufficient intensity to consume surface fuels to prevent reburning but low enough so that handcrews can directly engage with the fire. Constraints can be same as rules of engagement for resources regarding the main fire front	none
Suppression difficulty index	– Index quantifying the difficulty to engage in line construction activities given vegetation and topo-edaphic conditions, proximity to road or trail access, among other factors	Rodriguez y Silva et al. (2014)
Accessibility	– Specific location and conditions of tactical assignment relative to roads or other improved features to establish distance to safety zones and other logistical features, limitations for resource use, or need for helicpoter transport or logistical support	van der Merwe et al. (2014) restrict travel for point protection
Environmental Hazard Rating	– Relative hazard of assignment given fire environment, which is a function of predicted fire behavior, landscape location of task, and timing of task completion	Arrubla et al. (2014) by setting user risk preference

fires, and primarily relate to fire behavior and resource mobility (Table 3). Resource constraints capture factors associated with the type of personnel responding to large fires, and include but are not limited to their availability for use, travel time to the incident, production rates at varying tasks, costs of employment and rules of engagement with the fire (Table 4). The last group of constraints influencing decision makers, and therefore should be included in decision support tools, are operational standards or conventions (Table 5). These define how tasks are implemented (order of operations) during large fire management, capture many safety guidelines, and define the expectations for completing tasks to an appropriate standard. Many of these constraints are defined by the local agency where the fire occurs and therefore are not the same across all incidents, primarily varying by vegetation type rather than geographic location. Together, these constraints define many important variables that influence how and when resources will be used throughout these long-duration incidents. We further elaborate on these constraints in the following paragraphs as we describe their use in OR models.

Environmental constraints are dynamic in space and time as related to both landscape conditions and fire behavior. In many cases, landscape conditions relate to the difficulty or safety of accomplishing assigned tasks, an important component to capture, as discussed further under resource constraints (Rodriguez y Silva et al., 2014). The landscape conditions also define the suite of opportunities to create a contiguous control line around a fire, something fire managers must determine by leveraging landscape or man-made features most likely to control a fire. To date, no OR model constrains line locations to specific portions of a landscape because they generally assume direct attack is possible anywhere on the landscape despite potential hazards, especially regarding access or egress to escape routes and safety zones (Butler, 2014).

Fire behavior significantly influences strategic and tactical response decisions on large fires, providing important inputs to OR models. Fire behavior predictions can provide spatially explicit estimates of fireline intensity, flame length, rate of spread, and the probability or timing a fire will reach a specific point on the landscape. In particular, fire spread rates will determine the likelihood that responders can complete a control line prior to fire arrival when pursuing a suppression strategy, and the intensity of the fire at the fireline will influence what resources can effectively engage with the fire at that point (Andrews et al., 2011). At a strategic scale, the probability of fire reaching particular points across the landscape support decisions regarding an appropriate response strategy given the distribution of valued resources and assets. Each of these fire behavior predictions represent fundamental inputs to current decision processes, as well as the decision framework we propose.

The minimum travel time algorithm incorporated into FlamMap (Finney, 2006) has been used in recent OR models to quantify arrival time and fire behavior across landscapes. This determines where and when available resources can complete an effective control line (Wei et al., 2011; Belval et al., 2015). FlamMap can handle multiple fires, or backing or flanking fire behavior, under constant fuels and weather scenarios for the simulation period. However, a user could evaluate multiple scenarios by simulating varying conditions independently of each other. *FARSITE* can be used to simulate single or multiple fires for shorter 3–7 day periods accounting for time varying weather conditions (Finney, 2004). FSPro offers greater flexibility in modeling a single fire for longer durations using time series analysis to account for weather and wind information, beyond the reliability period of weather forecasts, to calculate conditional burn probabilities for a single fire and time period (Finney et al., 2011). Adding to fire behavior forecasting uncertainty is the influence fire management operations have on fire behavior (Wei et al., 2011; Duff and Tolhurst, 2015), which can be subjectively included through various user interjections, but may be negligible except along backing or flanking fires that are not estimated from empirical data in current fire behavior models (Rothermel, 1972).

Table 4
Operational resource constraints on decision variables.

Constraint (influence)	Sub-category	Description	Examples of use in models
Resource pool	Availability of operational resources	– Many resources are nationally available for incident response so variability changes dependent on fire activity; Resources can be transferred to incidents with a higher priority	All models have a defined set of available resources for line construction or point protection
	Overhead (e.g. IMT and staff, Strike Team Leaders, Task Force Leaders, Division Supervisors)	– Incident Command System (ICS) structure requires hierarchy of overhead	
	Support staff	– Logistical support (e.g. camp crews, supply cache, catering), medical support, etc.	
Resource travel time	To Incident Command Post (ICP)	– Travel cost incurred by incident but no production received; includes check-in and demobilization processes and there influence on incident assignment length. Length of travel also influences responder exposure to driving hazards	Wei et al. (2011)
	To daily fireline assignment	– Travel from ICP or alternative camp to fireline assignment location that reduces time for productive activities	Belval et al., 2015; Hu and Ntaimo (2009); Wei et al. (2011, 2015)
Incident assignment length	Number of days on active fireline assignment	– 14 days in U.S. before 2 days off at home unit is required	Wei et al. (2017)
		– Option of one day off followed by additional 7 days of work before 2 days off	
Span of control		– Establishes overhead needs for managing resources safely (could be a limiting factor for utilizing additional resources)	none
		– Typically limited to 4 or 5 resources under direct supervision by an individual. Overhead requirements can be met by higher grade (qualifications) personnel	
Resource production rates (day and night operations)	Handline	– Length of control line constructed per unit time (e.g., hour) by type (I, II IA, II).	Belval et al., 2015; Donovan and Rideout, 2003; Hu and Ntaimo (2009); Wei et al. (2011, 2015)
	Dozer/plow line	– Length of control line constructed per unit time (e.g., hour) by type (6–8)	Arrubla et al. (2014); Donovan and Rideout, 2003; Hu and Ntaimo (2009); Ntaimo et al. (2012, 2013)
	Engines	– Length of control line constructed per unit time (e.g., hour) various sizes (Type III – VI) with different water holding capacity and crew size	Donovan and Rideout, 2003; Hu and Ntaimo (2009); Wei et al. (2011, 2015)
	Roadside brushing, preparation for burnout operations	– Length of control line brushed or prepared per unit time (e.g., hour) by handcrew type and distance into control perimeter	none
		– Length constructed per unit time (e.g., hour) by equipment type and distance into control perimeter	none
	Wet line	– Length constructed per unit time (e.g., hour) by engine type. Limited to light fuels	none
	Point protection	– Number of resources needed to protect various HVRAs.	none
	Logistical-features	– Type of resources and length of need to create these features (production function)	none
	Burnout operations – lighting	– Distance of control line per unit time (e.g., hour) the resource can safely and efficiently ignite	none
	Burnout operations – holding	– Distance resource can safely hold control line (5–7 m spacing for individual crewmembers).	none
	Burnout operations – securing	– Distance resource can safely secure control line (5–7 m spacing for individual crewmembers)	none
	Water support installation – ground	– Hose lays, pumps, relay ponds	none
	Mop-up (area based for containment and control of fire)	– Dry mop-up	none
		– Wet mop directly from engines	none
		– Wet mop from hoselays and pumps	none
	Control line reinforcement	– Retardant	none
	Control line intensity reduction	– Water drops	none
	Crew transport or supply delivery	– Is it a full day allocation or part time use?	none
	Rehabilitation	– Control lines; roads; drop, safety, and deployment zone. Only features directly related to tactical response	none
	Dust abatement	– Length of road or helibase water tenders can effectively cover	none
	Aerial reconnaissance or crew transport	– Alternative uses of helicopters	none
Synergies	Benefits in production when various resources work together	– Strike teams – usually four to five of the same resource types working as a unit	Mees and Strauss (1992); Wei et al. (2015)
		– Task Force – usually four to five different resource types working as a unit	
Resource cost	Handcrew	– By type (I, II IA, II)	Belval et al., 2015; Donovan and Rideout, 2003; Hu and Ntaimo (2009); Wei et al. (2011, 2015)
	Mechanized equipment	– By type (bulldozers, excavators, road graders)	Arrubla et al. (2014); Donovan and Rideout,

(continued on next page)

Table 4 *(continued)*

Constraint (influence)	Sub-category	Description	Examples of use in models
			2003; Hu and Ntaimo (2009); Ntaimo et al. (2012, 2013)
	Airtankers	– By type (payload capacity)	none
	Helicopters	– By type (I–III)	none
	Engines	– By type (III–VI)	Donovan and Rideout, 2003; Hu and Ntaimo (2009); Wei et al. (2011, 2015)
	Water tenders	– By type (payload capacity) and vehicle age (reliability)	Hu and Ntaimo (2009); Wei et al. (2011, 2015)
	Water support systems	– Depreciation of hose lays, fittings, pumps, relay ponds	none
	Overhead	– ICS command structure requires hierarchy of overhead including IMT staff and analysts	none
	Support staff	– Various needs dependent on resource abundance	none
Rules of engagement	Limitations on tactical assignments	– Constraints on resource use primarily for safety but also resource capabilities	van der Merwe et al. (2014)
	Daily tactical assignment length	– 2:1 work to rest ratio cannot be exceeded (Includes travel to and from fireline)	most, by limiting number of hours of production
	Fire behavior	– Limitations on fire intensity or rate of spread a resource can actively engage with the fire during their tactical assignment	Wei et al. (2011)
	What fireline assignments are resources qualified to conduct?	– Many tactical assignments are not relevant to some resources or are too complicated for them to implement (e.g. lighting of burnouts often limited to Type I handcrews, but may include Type II IA and some engine strike teams	van der Merwe et al. (2014)
	Fireline assignments in remote locations or difficult terrain	– Often limited to crews with special training (e.g. ability to work with helicopters for supply deliveries) or physical capability. Similarly, some resources are prepared for overnight stay in remote locations. Best exemplified by Type I crews	none
	Travel restrictions	– Limitations on portions of landscape resources can access. For example, engines cannot travel handlines or many dozer lines, and some larger engine types (e.g., III and IV) often cannot travel mountainous roads thus have to rely on Type VI engines	Mees and Strauss (1992); van der Merwe et al. (2014)
	Allowable evacuation time	– How much evacuation time from fireline assignment to safety zone is acceptable for a resource? Can be dependent on expected fire behavior or fixed	none
	Crew transport or supply delivery	– Helicopters used to transport crews and supplies to remote locations. Establish a rule set such that any crew working remotely (e.g., > 10 km by foot) requires transport and resupply by helicopters	none
	Triage	– Establish a rule set regarding the likelihood that a particular HVRA can be safely protected from the fire	Arrubla et al. (2014) as function of HVRA exposure; van der Merwe et al. (2014) as a function of additional work prior to fire arrival
Experience		– Crews become more efficient with increased familiarity of tactical assignment and incident. Most evident with similarity in fireline assignment, location, etc.	Fried and Fried (1996); Petrovic and Carlson (2012)
Resource quality		– Evaluation of productivity and safety of resources to be incorporated into fireline assignments and demobilization decisions	none
Injuries, equipment failures		– Penalty on productivity due to unforseen events such as injuries or equipment failure.	none
Control line success		– Probability of line holding depending on type and fire behavior	Mees and Strauss (1992)

Decision makers often rely on indirect attack with burnout operations to secure control lines, and therefore large fire OR models must incorporate projections of burnout fire spread and intensity to represent fire behavior on large fires more accurately, especially since these operations may unintentionally compromise control lines.

Large fire management decisions are constrained by various aspects of responding resources, ranging from resource availability and productivity to rules of engagement (Table 4). Constraints on responding resources are more numerous and complex because they attempt to capture the multitude of tasks performed by a variety of suppression resources. These types of constraints have received greater attention in wildfire OR models relative to the other constraints we have identified (Table 4). The most commonly captured resource constraint has been control line production rates that, when combined with resource cost, determines their use efficiency (Donovan and Rideout, 2003). OR models rely on generalized line production rates with additive effects of additional resources (Hirsch et al., 2004; Broyles, 2011), despite recent empirical evidence suggesting these are significant overestimates when applied in the large fire management context (Holmes and Calkin, 2013; Katuwal et al., 2016). OR models also assume substitutability of responding resources for line production, which may or may not be appropriate for this and other common large fire management tasks, and routinely disregard synergies among resources. These assumptions may be particularly limiting since fire managers commonly deploy responding resources to tactical assignments as strike teams or tasks forces because of the potential benefits to efficiency for achieving specified tasks. For example, indirect line construction with burnouts benefit from retardant delivered by aerial resources because it could reduce the potential for escape, and engines commonly support handcrews for line holding and mop-up. Other common constraints on large

Table 5
Operational standards influence on decision variables.

Constraint (influence)	Description	Examples of use in models
Responder safety	– Responders require escape routes and saftey zones to be located within an acceptable and acheivable evacuation time on large fires, including when a multi-frontal attack is employed during indirect attack. Become trigger points for disengagement during fireline operations. This will vary by resource type and physical fitness	none
Job Hazard Rating	– Varying levels of exposure to hazards should be expected for different tasks. The relative hazards of tasks should be quantified to evaluate the overall exposure index of the chosen strategy	Arrubla et al. (2014) via a risk-level preference defined by user
Order of operations	Necessary order of progressive fireline assignments	none
	Control line construction: 1) Physical construction, 2) hazard tree mitigation, 3) hoselays (handlines or dozer lines), 4) line securing, 5) mop-up to control, 6) rehabilitation	none
	Burnout operations: 1) Control line preparation, 2) hazard tree mitigation, 3) hose lays, 4) Ignition, 5) line holding, 6) line securing, 7) mop-up to control, 8) rehabilitation	
Safe line construction	– Safety guidelines recommend direct lines are anchored to prevent egress from being compromised if a fire burns behind where the line is being constructed	Fried and Fried (1996); Hu and Ntaimo (2009)
Containment standards	– Distance within fire perimeter requiring mop-up before fire is considered contained (5–20 m). Variation dependent on fuel conditions and forecasted fire weather	none
Control standards	– Distance within fire perimeter requiring full mop-up before fire is considered controlled (30–100 m). Variation dependent on fuel conditions, forecasted fire weather and distance to HVRAs such as WUI	none
Rehabilitation standards	– Amount (distance, area) by type so cost of this requirement can be accounted for in tactical assignment decisions	none
Burnout operation trigger	– Decision rules supporting the use of burnouts or backfiring	none
	– Preventing headfire from directly challenging control line. Can be determined from fire behavior simulations	none
	– Expediency of containing fire before fire weather changes towards more extreme conditions	none
	– Removing unburned fuels along fireline because most fire fronts are uneven	none
Anchored burnouts	– Preparation can occur well in advance of the flaming front and without an anchor point as long as escape routes are not compromised	none
	– Ignition should be constrained to start at an anchored point connected to a secure control line to prevent an escaped fire or compromised egress	none
Completed tasks	– Forecasted date of completion of various tasks is necessary to determine where to allocate or release resources when they become available	none

fire decisions include scarcity and arrival time, which are commonly captured in OR models focused on IA (Petrovic et al., 2012). Once acquired, large fire management models still allocate resources to direct attack because IA model formulations are extended to large fires (Wei et al., 2011; Belval et al., 2015), thereby excluding many tactics common to large fire management (e.g., indirect attack, burnouts). For all tasks, there are rules of engagement that establish thresholds of acceptable fire intensity or flame length that responding resources can safely engage with the fires, as well as their implied effectiveness under such conditions, which have been incorporated into some OR models (Andrews et al., 2011; Wei et al., 2011; Belval et al., 2015). However, these rules need to be expanded to capture the full breadth of tasks employed by all models to more accurately represent the complexity of decisions made during large fire management.

The third set of constraints relates to operational standards or conventions that circumscribe fireline tasks generally intended to improve the safety of the working environment (Table 5). These operational standards or conventions developed over more than 100 years of fire suppression history in the U.S., most frequently in response to an observed adverse event. For example, there are established conventions that fire managers typically complete before they are confident enough to consider control lines contained or controlled, such as mop up 30–100 m within the fire perimeter; a process that amounts to significant resource use (Katuwal et al., 2017). Many tasks commence with a pre-defined order of operations that decision makers routinely consider during large fire management, and therefore need to be included in any OR model attempting to be operationally relevant. Other standards include constraining the line production rate to anchored positions (Fried and Fried, 1996; Hu and Ntaimo, 2009), physical safety features (Butler, 2014) and trigger points for disengagement should hazardous conditions arise (Table 5). Few of these constraints have even been considered in OR models to date despite representing how actual tactical operations occur on large fires.

5. An expanded decision support system

Fire managers must manage risk and uncertainty while minimizing decision biases to improve the safety and effectiveness of large-fire response. Decision support systems support risk-informed decision making and can provide an objective means for analyzing response options, monitoring decisions and outcomes, and documenting the decision process for future learning. The Wildland Fire Decision Support System (WFDSS) is the most widely used decision support system for large fire management in the U.S., and was explicitly developed to support risk-informed decision making (Calkin et al., 2011b; Noonan-Wright et al., 2011). However, WFDSS does not promote examination of multiple response options that support tradeoff analysis and decisions, does not attempt to optimize the tactical response, and user-generated objectives are unclear. Additionally, WFDSS does not document the decision process or deliberations about the employed strategic and tactical response, presumably chosen among several options. All these components are necessary for improving the efficiency of wildfire response strategies and tactics.

As we look towards the future of large-fire management decision support, there is a need to align a hierarchy of decisions beginning with pre-incident planning and continuing through the development of optimal response strategies and tactics. Fig. 1 depicts the framework for developing a dynamic, multi-response model capable of supporting large-fire management decisions for various resource objectives. Progression from left to right represents a transition from broader-scale decisions and strategies to incident-level tactical decisions and response objectives. An aggressive suppression response remains a viable alternative within this model, although with improved safety and effectiveness through more advanced risk-informed decision making.

5.1. Pre-incident planning

Pre-incident planning can provide a response spectrum that streamlines problem formulation by facilitating discussions of fire

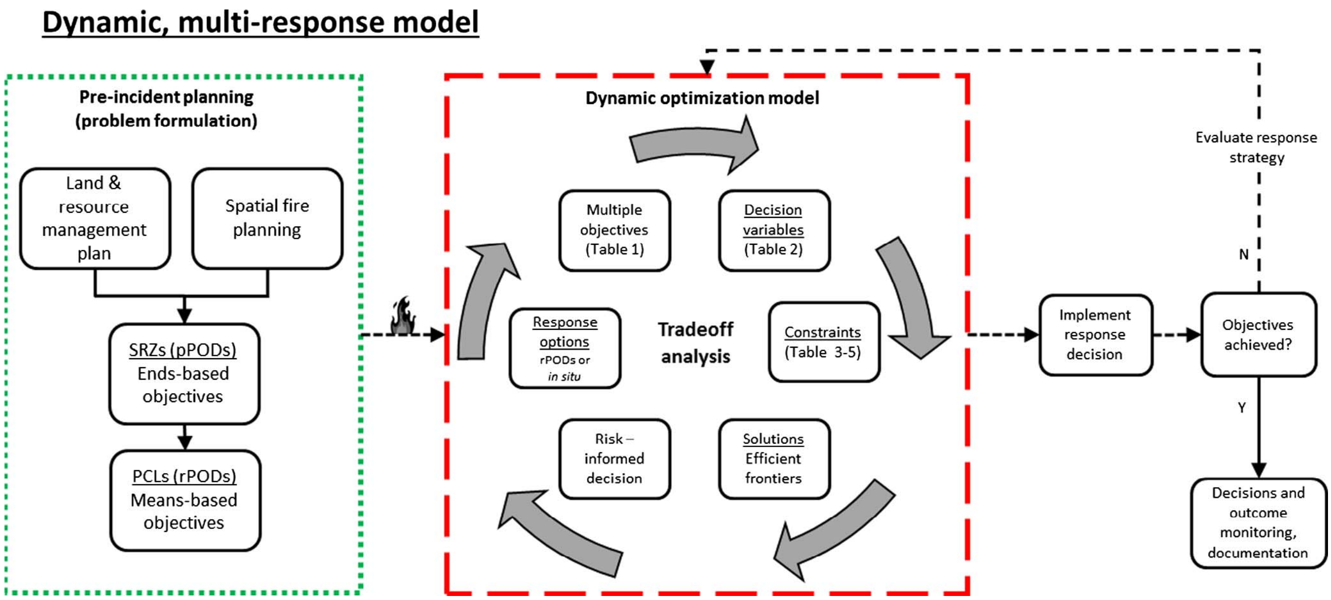

Fig. 1. A depiction of the framework for developing safe and effective large-fire response in a new fire management paradigm. This process begins with significant pre-incident planning to support clear articulation of resource and fire management objectives, followed by a dynamic, multi-response model facilitating a tradeoff analysis for various response options. Once the decision makers select the desired strategic and tactical response, the operation is continually monitored and decisions are evaluated so model adjustments can be made in response to uncertain conditions within the fire environment. The decision process and outcomes are monitored and documented for continuous learning by fire managers and their supporting agencies.

effects within the context of LRMP objectives or requirements in advance of an ignition. This process begins with spatial fire risk assessments and spatial fire planning that bridges existing gaps between LRMPs and fire management plans (Thompson et al., 2011; Scott et al., 2013). Fire managers and resource specialists summarize the exposure of HVRAs, such as the wildland urban interface (WUI), municipal watersheds, and non-market resources to wildfires (Calkin et al., 2010; Venn and Calkin, 2011; Haas et al., 2013; Warziniack and Thompson, 2013), into planning-scale potential wildfire operational delineations (pPODs). These pPODS are typically defined by watershed boundaries (ridges) and major roads; landscape features often used to control a fire. These delineations often result in smaller pPODs in areas with higher exposure of HVRAs because there are more built assets to protect and more man-made structures (i.e. roads) to leverage as control lines. The converse is observed in wilderness areas in more remote locations. Managers and specialists then categorize pPODs as one of several strategic response zones (SRZ), creating a spatially explicit response spectrum across the landscape (Meyer et al., 2015; North et al., 2015; Thompson et al., 2016a). This gradient in response spans from full protection next to communities, to maintenance zones where resource specialists and fire managers anticipate fire to have positive net benefits. Ultimately, SRZs provide ends-based objectives for managing wildfires well in advance of ignition, supporting problem formulation and reducing the time to develop, communicate and deliberate decisions following an ignition.

Pre-incident planning could further support large-fire management by spatially identifying operationally relevant large-fire management features. Researchers have developed methods to identify potential control lines (PCLs) across landscapes based on an assessment of features commonly observed along historical large-fire boundaries (O'Connor et al., 2017). These PCLs form the basis for creating response-scale potential wildfire operational delineations (rPODs), or fire containers, that form a continuous boundary that maximizes containment probability and likely minimizes responder exposure, dependent on fire weather conditions. Escape routes and safety zones are other important safety features in large-fire management that can be identified across landscapes before an ignition (Butler, 2014; Campbell et al., 2017). These methods can be extended to helispots, water drafting sites (often already identified on maps), drop zones (meeting locations, supply delivery points), and deployment zones (cleared areas that can be used for fire shelter deployment). This process demonstrates state-of-the-art pre-incident planning and provides a critical and necessary step towards improving large-fire management because it reduces time-constrained decisions, provides greater situational awareness, and can reduce unnecessary responder exposure by minimizing attempts to suppress a fire at locations with a low-probability of success.

The development of means-based objectives for the various response options considered are at least partially derived from pre-incident planning. Connecting PCLs into rPODs, *in situ* or pre-incident, allows for quantification of the amount, type and characteristics of control lines suppression resources must build. This estimates the amount of work necessary to create a containment boundary. Further, decision makers can aggregate rPODs to manage ignitions in conjunction with LRMP and spatial fire planning objectives. By comparing the spatial location of containment lines and HVRAs, the model could evaluate, and decision maker could choose, a response option that minimizes attempts to control a wildfire at a location with a low-probability of success to protect a specific HVRA, unnecessarily exposing responders to hazardous conditions. Instead, fire managers could allocate resources to point protection of these HVRAs as they pursue alternative containment lines. All of this information is necessary for a dynamic, multi-response model designed to integrate fire behavior simulations with optimization procedures that schedule the acquisition, allocation and demobilization of responding resources.

5.2. Tradeoff analysis

Upfront planning coupled with a flexible and dynamic OR model offers greater opportunity for decision makers to evaluate multiple response options under varying assumptions or conditions. This process avoids undue sensitivity to parameters and allows decision makers the ability to game out the worst and best case scenarios in their effort to make the best risk-informed decision possible. The first step in the tradeoff analysis is to overlay predicted daily fire spread contours on a network of potential control lines or rPODs to identify the response options. The control lines or container networks can be developed *in* *situ* as described previously in pre-incident planning, or as an aggregation of already defined containers. In either case, the intended control perimeter can be delineated based on various line placement constraints and integrated into the probability of success of a particular strategy. *FARSITE* offers some ability to conduct this analysis, but the operational resource model within this simulation system is too basic to produce realistic tactical response scenarios and therefore needs to be incorporated into more advanced resource production models (Finney, 2004; Duff and Tolhurst, 2015). Through this process, the decision-maker choses a suite of response options that are integrated into the dynamic optimization model that accounts for the information contained in Tables 1–5.

The tradeoff analysis requires the model to forecast the full breadth of management actions, but once a response strategy has been chosen the model needs to be dynamic. Maintaining the capacity for situational updates of completed tasks, resource productivity, resource availability, weather forecasts, and the physical fire characteristics could reduce accumulated errors from previous operational periods. Documenting these changes can also improve model estimates for the current and future incidents through model adjustments and accuracy assessments. Designing the system with the intent of decision-maker interaction also allows for continued evaluation of *in situ* alternative response strategies and tactics such as whether to increase responder abundance to protect specific HVRAs given their potential exposure to the approaching fire. While we focused on operational resources only, we acknowledge that logistical support staff are important to successful large-fire management. While we have described the majority of decisions affecting risk-informed decision making, as this framework continues to be implemented additional sub-routines can be created to account for this and other factors associated with managing these complex decision environments.

6. Discussion

We have described a framework for developing safe and effective response strategies and tactics for large wildfires. This framework integrates decisions made at multiple levels within land and fire management organizations and is intended to support risk-informed decisions. Acknowledging fire's inevitability and integrating governing plans is the first in a series of linked steps necessary to improve the decision making process. Several U.S. National Forests have begun this process through pre-incident planning by developing strategic response zones and potential wildland fire operational delineations (Thompson et al., 2016a). By including an operational research (OR) model, decision makers will be able to assess tradeoffs based on robust analytical methods that could minimize responder exposure while achieving strategic and tactical objectives. WFDSS provides a well-designed foundation that can be expanded to include this model, leveraging the benefits of accrued decision support tools and information important to the decision process. WFDSS is also familiar to fire managers and decision makers in the Unites States, increasing the likelihood that these new analyses will enter the decision making process. Eventually, this system could be linked directly with the Resource Ordering and Status System to balance resource allocation across multiple incidents at the regional and national-level (http://famit.nwcg.gov/applications/ROSS). However, a concerted effort by the fire management community to invest in assessment, monitoring, and implementation of the decision process, outcomes and supporting models are both prudent and necessary given the rising costs associated with large fire management.

In particular, fire behavior predictions need to be improved to more accurately represent real-world large-fire situations. Our proposed framework requires daily fire spread contours which can be obtained from *FARSITE* when reasonable fire weather data is provided (Finney, 2004). This has generally been limited to a three-day horizon because there is increasing uncertainty in fire weather forecasts beyond this period. FSPro was designed to model fire spread contours as the probability of fire reaching a point on the landscape based on historic weather streams directly relevant to the fire area, but does not provide daily spread contours (Finney et al., 2011). Combining these methods has potential, but quantifying the probability distribution for daily fire spread becomes increasingly uncertain with long-term forecasted weather, especially since large-fires can burn for months. Additionally, there is a need to integrate recent advances in our understanding of wildland fire behavior (Finney et al., 2015), and follow up with comparisons of fire behavior predictions with field observations to validate or improve fire behavior prediction systems.

Another important step forward would be a concerted effort for empirical evaluation of the assumed benefits derived from commonly employed response strategies and tactics. For example, recent research suggests helicopters do not contribute significantly to the production of control lines on large fires, but the benefits and use of these resources for other tasks has not been evaluated (Holmes and Calkin, 2013; Katuwal et al., 2016). Fixed-wing aerial resources (air tankers) are effective at IA in grass or low-shrub fuels (Plucinski et al., 2007, Ganewatta and Handmer, 2009), but recent evidence demonstrates they are dominantly used during large-fire management in forests, and often during periods when fire behavior is such that suppressant or retardant may have a limited effect on fire behavior (Thompson et al., 2013; Calkin et al., 2014; Stonesifer et al., 2016). Inefficient utilization of resources may prevent their availability to respond to fire ignitions in fuel types where they are more likely to be effective, and may unnecessarily expose them to hazards common during fire management (Butler et al., 2015). Investment by the interagency fire management community into these and other aspects of large fire management has the potential to drastically increase responder safety and effectiveness while reducing large fire management expenditures.

Successful implementation of this framework relies on an improved partnership between decision makers and researchers. Researchers should be cautious not to focus on generating information that is irrelevant to large fire decisions. Existing OR models not only fail to capture many realistic tactics and associated rules of engagement on large fires, but they also appear to be misrepresenting the decision process as previously described (Duff and Tolhurst, 2015). A clear starting point for addressing the first problem is this exhaustive and transparent articulation of objectives, decision variables and constraints (Tables 1–5). A tradeoff analysis and frontier generation, as well as the pre-fire planning, could help overcome the second problem as this would be more representative of the large fire decision process (Zimmerman, 2012). However, decision makers need to be more transparent in their decision process to support research efforts, as we currently have little to no information on what response alternatives were analyzed for any given large fire incident or what questions decision makers even asked to derive their response decision (Calkin et al., 2011b; Noonan-Wright et al., 2011). Increased transparency would provide valuable information for assessments, and allow researchers to focus on identifying key gaps in decision processes and questions that managers should be asking but are not. Given existing time pressures and the complexity of the large fire decision environment, obtaining this information likely rests on the shoulders of researchers integrated with decision makers to document their process. This renewed partnership would leverage both parties' skillset to a greater degree, with the potential to improve contemporary large fire management efforts.

The increasing consensus that we must learn to live with fire to meet ecological, economic and social needs (Moritz et al., 2014; Schoennagel et al., 2017), is pressuring fire managers to transition to an ecological fire management paradigm (Ingalsbee, 2017). Expanding the right kind of fire at the right place and time, while still protecting valued resources and assets, relies largely on fire managers changing default strategies and business as usual practices (Thompson et al., 2015). The framework presented here outlines a decision process, as well as advance decision support tools, that better capture the complexity of the large fire decision environment and expands risk sharing across the agency and among researchers and managers alike. Using best available data and analytics, we believe this framework will ease the paradigm shift by improving decisions and creating a more transparent decision process. Ideally, this will allow agencies to emphasize the decision process over outcomes, especially since bad outcomes may arise from good decisions and good outcomes from bad decisions. Doing so requires a robust decision support framework flexible enough to meet the needs of a response spectrum that is dynamic in space and time, such as the one we have outlined here.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2017.08.039.

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