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Review

Cohesive fire management within an uncertain environment: A review of risk handling and decision support systems

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A R T I C L E I N F O

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A B S T R A C T

Wildfire management has been struggling in recent years with escalating devastation, expenditures, and complexity. Given the copious factors involved and the complexity of their interactions, uncertainty in the outcomes is a prominent feature of wildfire management strategies, at both policy and operational levels. Improvements in risk handling and in risk-based decision support tools have therefore a key role in addressing these challenges. In this paper, we review key systems created to support wildfire management decision-making at different levels and scales, and describe their evolution from an initial focus on landscape-level fire growth simulation and burn probability assessment, to the incorporation of exposure and economic loss potential (allowing the translation of ignition likelihood, fire environment – terrain, fuels, and weather – and suppression efficacy into potential fire effects), the integration with forest management and planning, and more recently, to developments in the assessment of values at risk, including real-time assessment. This evolution is linked to a progressive widening of the scope of usage of these systems, from an initial more limited application to risk assessment, to the subsequent inclusion of functionality enabling their utilization in the context of risk management, and more recently, to their explicit casting in the broader societal context of risks and decisions, from a risk governance perspective. This joint evolution can be seen as the result of a simultaneous pull from methodological progresses in risk handling, and push from technological progress in wildfire management decision support tools, as well as more broadly in computational power. We identify the key benefits and challenges in the development and adoption of these systems, as well as future plausible research trends.

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1. Introduction

Uncertain and highly unpredictable factors, such as weather forecasts, performance of suppression resources, and fire behavior, spread and effects, are the basis of fire management and policy decisions, across multiple levels and scales. Theoretical and computational progress in the last four decades has enabled the development of risk-based Decision Support Systems (DSS) that contribute to improve those decisions, namely by facilitating a structured assessment of the outcomes and costs associated with alternative policies, budgets, and suppression resource mixes.

In recent years, several authors have updated the state of the art on these tools and related challenges. Minas et al. (2012) have updated the review of Martell et al. (1998) on operations research methods applicable to wildfire management. Thompson and Calkin (2011) organize and align sources of uncertainty with decision support tools and methodologies, in order to facilitate cost-effective, risk-based wildfire management and planning efforts. Mavsar et al. (2013) present the economic efficiency analysis theory of fire management measures and use it as a framework to review four fire management DSS in use in America and Europe. Papadopoulos and Pavlidou (2011) make a comparative review of wildfire simulators and Sullivan (2009b) presents a comprehensive survey and review of surface fire spread simulation models. Indeed, some pre-defined spread model is incorporated in most of wildfire simulation models to simulate the behavior of fire across a landscape (Thompson and Calkin, 2011). Bettinger (2010) describes the methods used to integrate wildfires into forest planning models, using operations research techniques, going back to the seminal work of Van Wagner (1979), while more recently Pasalodos-Tato et al. (2013) review the use of decision support tools to address risk and uncertainty in forest management planning.

Our review adopts a higher-level perspective to provide a broader and more complete view of the evolution of the field. We concisely present several important risk-based decision support models for fire management, on the one hand highlighting their usefulness within the scope and the purposes that guided their development, but on the other rendering explicit a number of limitations that they present. Some of these limitations have also been discussed recently, although in a fragmented way, in the literature on challenges in the development and deployment of risk-based decision support systems. We bring together this set of observations, and highlight what seems to us to be an important trend of broadening of concerns from risk assessment, to risk management, to risk governance. This trend frames an increasingly ambitious utilization of these systems, gradually and successively broadened to address each of those areas of concern. This overall evolution pattern is the result of simultaneous methodological progress in risk handling, as well as specific technological progress in wildfire management decision support tools, and generic technological progresses in computation.

The remainder of the paper is structured as follows: in Section 2, we describe several fire growth simulators developed in recent decades in multiple parts of the world, and their connections with different wildfire management DSS based on economic models, as well as developments in the integration of forest and fire management, and more recent efforts aiming at going beyond economic models; in Section 3, we characterize the trend of broadening of risk handling concerns from risk assessment, through risk management, to risk governance, in close connection with the previous section; in Sections 4 and 5 we close the paper, with a discussion and with the presentation of conclusions and suggestions for future work, respectively.

2. From fire growth simulation to economic models and beyond

2.1. Fire growth simulation models

A number of wildfire growth simulation models have been developed over the years (Table 1). Explicit spatial simulation of fire growth requires a fire spread model and the description and mapping of vegetation (fuel) as per the typology required by the spread model. Consequently, spatial fire modeling has been preceded by the ability to estimate fire behavior characteristics for a given point or location from a set of static fuel, weather and slope conditions. Fire spread models usable by fire managers are either semi-physical or empirical in nature. The Rothermel (1972) model is the best known of the former type and is widely used, being at the core of the U.S. fire modeling systems, from the stand – e.g., BEHAVE (Andrews, 1986), now BehavePlus (Andrews, 2014) – to the landscape-level – e.g., FARSITE (Finney, 1993, 2004). Rothermel's model has also been adopted for fire growth simulation elsewhere, e.g., CARDIN (initially based on BEHAVE and later named "Visual Cardin") in Spain (Millan et al., 1991; Martin-Fernández et al., 2002; Rodríguez y Silva and González-Cabán, 2010) and in the module of fire simulation of the KITRAL system in Chile (Julio et al., 1995).

Canadian and Australian fire growth simulators depend on empirical fire spread models and systems (Noble et al., 1980; Forestry Canada, 1992). The Canadian Prometheus has been in development since 1999 (Tymstra et al., 2010). The Australian SiroFire was launched in 1994 (Coleman and Sullivan, 1996) and has now been replaced (Sullivan, 2009b) by PHOENIX Rapidfire (Saeedian et al., 2010; Duff et al., 2012) at the University of Melbourne as a component of a risk management model, being developed by the Bushfire CRC for southern Australia (Tolhurst et al., 2008; Taylor and Freeman, 2010).

Vector-based simulation approaches for fire growth like those based on Huygens principle produce much more realistic fire shapes than raster-based simulations, or cellular automata, among other alternatives (French, 1992; Sullivan, 2009b; Tymstra et al., 2010). Raster-based models deal with heterogeneous fuels and weather better than vector-based models (French et al., 1990). Nevertheless, and although the procedure varies, all the existing North American and Australian fire growth simulators implement Huygens approach (Cechet et al., 2014). Given our focus on systems used by practitioners, there are several other important models

Table 1
Review of the characteristics of cited fire modeling systems (fire behavior, fire spread, and probabilistic fire spread simulators).

Name	Origin/ year	Primary attributes	Inputs	Outputs	Spread model/math. models	Deterministic/ stochastic	Planning context and decisions supported	Duration	Fires considered	Simulation type	Type of burn probability	Source of variation[l]	References
BehavePlus[b]	USA 1983[c]	Fire behavior prediction and fuel modeling – Constant variation in time – Uniform variation in space (runs in a PC or Smartphone)	Interactive user input (generally ranges of values)	– Tables – Graphs – Simple diagrams	Over 40 mathematical fire models for ignition and tree mortality probability, crown scorch height, surface and crown fire behavior, maximum spotting distance, safety zone size, point source fire size and shape, and fire containment	D	– Predicting the behavior of an ongoing fire – Fuel treatment planning – Training (fuel hazard, fire behavior) – Post-fire analysis	Elapsed time for size or spread distance	Individual fire	One fire, one constant weather scenario	NA	None	Andrews (2007) Andrews (2014)
Visual-Cardin used by SINAMI[d,e]	Spain 1989[f]	– Fire growth and behavior simulation modeling system – Initially based on BEHAVE, applies its algorithms in a discreet way to each pixel using raster maps (runs in a PC)	– Ignition area or line (set of pixels) with maximum slope and direction values, calculated from terrain topography (GIS) information – Fuel model in each pixel (cell) – Tree height, crown base height, and crown density – Fuel moisture and degree of protection – Wind speed and direction – Ambient temperature and humidity – Suppression resources spatiotemporal allocation	Maps of flame length and residence, directions, wind, fire line intensity, heat by unit area, and rate of spread (Rodríguez y Silva, 1999)	– 13 BEHAVE fuel models adapted to the Mediterranean ecosystems – Fire expansion is assumed to occur in a cardioid way (Cassini ovals), instead of elliptical as in BEHAVE – Simulation model through cellular automata (CA) using the more nearest neighbor (Rodríguez y Silva et al., 2014)	D[g]	– Predicting the behavior of an ongoing fire – Air and ground suppression actions planning – Fuel treatment planning – Post-fire analysis – Preventive forestry strategies design (Rodríguez y Silva, 1999)	–Minutes/hours of active burning with or without suppression –Proved to accurate for time intervals of 20 min (simulation/ reality emerged small discrepancies mean that the system should be updated every 20 min)	Individual fire (pixels ranging 20–50 m)	One fire, one weather scenario	NA	– Uniform wind speed and direction* – Air and live/ dead fuel moisture content, and wind protection* – Fuelscape[ax] *These values can be updated during the simulation	Millan et al. (1991) Rodríguez y Silva (1999) Martin-Fernández et al. (2002) Rodríguez y Silva and González-Cabán (2010) Rodríguez y Silva et al. (2014)
FARSITE[h]	USA 1993	– Fire growth and behavior simulation modeling system – Variation in time, diurnally and by day – Variation in space across the landscape – Heterogeneous conditions of terrain, fuels, and weather (runs in a PC)	– Spatial (GIS) fuel, terrain, etc. data – User-defined fuel moisture and wind	Maps of fire growth, perimeter, intensity, etc.	– Richards partial differential equations to propagate each vertex along the fire perimeter[i] – Mathematical fire models for surface fire spread, crown fire initiation and spread, spotting, and dead fuel moisture[j,k]	D[g]	– Fire and land management decisions – Air and ground suppression actions simulation	Long time periods: hours/day of active burning or number of days for the simulation	Individual fire	One fire, one weather scenario	NA	– Wind speed – Wind direction – Fuel moisture content – Fuelscape[ax]	Finney (2004) and Andrews (2007)
SiroFire[l,m]	Australia 1994	– Real-time bushfire spread simulator to help fire control officers predict the probable spread of a fire – Can consider suppressed sections of fire perimeter	– Topography (proprietary format with data derived from several GIS platforms) – Spatial fuel types (unburnable, other) – Fuel load and condition – Grass curing – Slope	– Map of the wildfire predicted spread across the landscape – Fire perimeter predicted at regular intervals – Wind direction changes can be incorporated in the prediction	– Rothermel's model (ellipse based on local fuel fire growth) configured for Australian grass and forest litter fuel – McArthur Forest and Grassland Fire Danger Rating meters – CSIRO Grassland Fire Spread Meter	D	– Predicting the behavior of an ongoing fire – Suppression actions planning (e.g., applying firebreaks) – Used mostly as fire-suppression training tool	One day[n] (from one day 9am until next day 9am)	Individual fire	Up to ten fires over the landscape, one weather scenario	NA	Throughout the day: – Temperature – Relative humidity – Wind speed and direction Does not: – make corrections for elevation of temperature and humidity	Coleman and Sullivan (1995) Coleman and Sullivan (1996) Sullivan (2009b) Papadopoulos and Pavlidou (2011)

(*continued on next page*)

Table 1 (*continued*)

Name	Origin/ year	Primary attributes	Inputs	Outputs	Spread model/math. models	Deterministic/ stochastic	Planning context and decisions supported	Duration	Fires considered	Simulation type	Type of burn probability	Source of variation[1]	References
		– Subsumed into PHOENIX Rapidfire (runs in a PC)	– Weather (temperature, relative humidity) – Wind speed/direction – Selected fire spread models (one for forests, one for grasslands)	– Spotting distance prediction[as] (not used to ignite new fires)	– Does not simulate crown fires – Does not simulate Spotfires							– incorporate fuel moisture lag time	
Prometheus[o,p] used by Burn-P3[q]	Canada 1999[r]	– Spatially explicit, deterministic fire growth simulation model – Complex fire environment and modeling parameters managed as scenarios – Modular design eases the integration with external applications[s] (runs in a PC)	– Spatial (GIS) topography (slope, aspect, and elevation) – Spatial fuel types (required) – Weather streams[t] – Spatial landscape grids[u] (option) – Wind speed/direction grids[v] (option) – Foliar moisture content – Fire type and duration – Fuel breaks (spotting is allowed[w])	– Statistics and map (vector and raster) views – Spread rate – Fuel consumption fraction burned and total (crown and surface) – Fire intensity – Spread distance – Fire area – Fire perimeter (at user-specified time step intervals)	– Richards partial differential equations to propagate each vertex along the fire perimeter[i] – FBP and FWI Systems (sub-systems of the CFFDRS[x])	D[y]	– Fire behavior training tool – Evaluate fire management alternatives/costs – Design of fuel management strategies for values at risk or in protected areas[z] – Fuel treatment planning[aa] – Large fires management – Post-fire analysis – Recovery planning[ab]	– One or many daily burning periods – Type and duration (only limited by the length of weather data) of the simulation	Individual or multi-fire simulation (Alberta generally uses 100 m grids (sometimes 25 m) for operational purposes)	One or multiple ignitions, under one or more scenarios	NA	Spatially across the landscape: – Fuelscape[ax,u] – Topographic conditions Spatially and temporally: – Weather conditions	Johnston et al. (2005) Opperman et al. (2006) Sullivan (2009b) Tymstra et al. (2010) Papadopoulos and Pavlidou (2011)
FSPro[ac] used by WFDSS[ad,ae] as RAVAR[af]	USA 2006	– Variation in time, by day – Variation in space across the landscape – Runs remotely for authorized analysts with internet access	– Spatial (GIS) fuel and terrain data – Current fire perimeter – Weather stations for fire danger and wind climatology	Map of probability of the fire reaching each point by the end of the simulation period	Minimum travel time (MTT) fire spread algorithm (Finney, 2002)	S	Suppression strategy development	Days to weeks of active burning or number of days for the simulation	Individual escaped fire	One fire, many weather scenarios	Conditional on current fire location and specified time period	– Wind speed – Wind direction – Fuel moisture content – Fuelscape[ax]	Scott et al. (2013) Finney et al. (2011a) Andrews (2007)
FSim[ag,ah] used by FPA [ai,ae]	USA 2008	Large-fire simulation system	– Landscape characteristics: Surface fuel model, aspect, elevation, slope, and canopy coverage – Historic Energy Release Component (ERC) – Wind Data from a representative weather station or from NARR GRID data (BAH, 2012)	– Spatially explicit burn probability maps and fire size distributions (Pacheco et al., 2013) – Intensity (via flame length), size, and impacts of escaped ignitions[o]) (BAH, 2012; Thompson et al., 2013b) – Fire intensity level table for each fuel model and percentage of treated surrounding area (-control and fuel treatment runs)[aj] (BAH, 2012)	– Minimum travel time (MTT) fire spread algorithm (Finney, 2002) – Combines weather influences, ignition probability, fire spread, and containment success submodels (Thompson et al., 2013a)	S	– Fire management plan development – Preparedness and response planning – Fuel treatment planning	Entire fire season	All large fire ignitions	All fires, all weather scenarios	Annual (full fire season)	– Wind speed – Wind direction – Fuel moisture content – Fuelscape[ax] – Ignition location and probability – Containment probability – Fire duration	Scott et al. (2013) Finney et al. (2011b) Finney (2007) BAH (2012) Thompson et al. (2013a) Thompson et al. (2013b) Notes[ah] (about FlamMap alternative): Finney (2006) Ager et al. (2007) Ager et al. (2011) Ager et al. (2013)
PHOENIX Rapidfire[ak] used[al] by FireDST[am]	Australia 2006[an]	Spatially and temporally explicit dynamic fire behavior and characterization model[ao] used operationally:	– Fuel types[ap] – Wind reduction factors – Fire history – Topography – Assets and values – Road proximity – Linear disruptions – Weather – Suppression resources	Maps of:	– CSIRO grass[ar], McArthur MK5[as] fire behavior models – Models for the effects of short to long distance spotting[aq] (<200 m to 30 km) by upper level winds	D	Component of the Bushfire risk management model[av], for use by fire agencies, land managers, town and land planners, and policy makers to explore the strength and the interaction[aw] of:	– Short to long periods of active burning (minutes to days) – 1/15 min time interval between perimeter spread cal-	Individual or multi-fire simulation	One fire and multi-fire under several management scenarios, from the Bushfire risk management model[av]	Fire likelihood at each cell location (when in multi-fire simulation) which can include the probability of a fire starting at the ignition point from	– Weather (wind speed/direction, temperature, humidity) – Fuelscape[ax] – Ignition location and probability – Suppression effects	Tolhurst et al. (2006)

Table 1 (*continued*)

Name	Origin/ year	Primary attributes	Inputs	Outputs	Spread model/math. models	Deterministic/ stochastic	Planning context and decisions supported	Duration	Fires considered	Simulation type	Type of burn probability	Source of variation[1]	References
		– to estimate the fire impact on specified values or assets – for training purposes – in real-time – for post-fire analysis (runs in a PC)		– Fire origin, extent, intensity, and frequency – Flame height and depth – Rate of spread – Ember density – Size (area) – Time to impact (in each cell) – Spotting[aq] (explicitly and deterministically modeled) – Convective output	– WindNinja[at] wind field – Wind-slope interactions, fuel accumulation rates, fuel moisture models, road impact, self-extinction and fire suppression – Fuel accumulation (time since fire) – Point spread modeling (Huygen's[au], discrete event CA)		– Prevention – Disaster preparedness and response – Recovery – Fire regime management	culations for fast/slow moving fires – 100–200 m grid size is usually sufficient for operational purposes (as small as 5 m for very detailed analysis)			historic data	– Fire conditions (e.g., spotfires increase the rate of spread, different fuel strata included or excluded as fire changes in intensity and over time)	Tolhurst et al. (2008) Sullivan (2009b) Tolhurst and Chong (2009) Saeedian et al. (2010) Taylor and Freeman (2010) Duff et al. (2012) Pugnet et al. (2013) Cechet et al. (2014)

[a] Relates to variability modeled with probabilities, or aspects which can vary in the course of the simulation, according to the system stochastic or deterministic nature.
[b] http://www.frames.gov/partner-sites/behaveplus.
[c] Considering the predecessor BEHAVE; BehavePlus 1.0 was released in 2001.
[d] SINAMI, Sistema Nacional para el Manejo de Incendios Forestales.
[e] ARCAR41 developed since late 1990s was abandoned.
[f] Cardin first version (used with ARCAR41[e] in the late 1990s in a strategic model for forest fire simulation and economic planning).
[g] Spotting has a stochastic component.
[h] http://www.firelab.org/project/farsite.
[i] Prometheus and FARSITE use the same method to propagate each vertex along the fire perimeter under heterogeneous conditions, but the models differ in the fire behavior modelling approaches and fuel typologies; Prometheus uses fuel types and the fire danger rating codes and equations of the CFFDRS,[x] whereas FARSITE uses fuel models[k] and is driven by Rothermel's model and related models[j] (Tymstra et al., 2010); both were compared by Opperman et al. (2006).
[j] FARSITE fire behavior models: Rothermel's (1972) surface fire spread model, Wagner's (1977) crown fire initiation model, Rothermel's (1991) crown fire spread model, Albini's (1979) spotting model, and Nelson's (2000) dead fuel moisture model.
[k] A complete reference can be found on the technical documentation: http://ced.berkeley.edu/faculty/ratt/tool_time/fire_lab/lab7/farsite_stuff/ ("FARSITE Technical References").
[l] The CSIRO bushfire spread simulator (http://www.csiro.au/Outcomes/Safeguarding-Australia/SiroFire-Overview.aspx).
[m] CSIRO has been working on a replacement for SiroFire called Spark, intended to be an open-source fire perimeter propagation engine that is platform independent and scalable across processors (Hilton et al., 2015).
[n] The output of one simulation could be used as the input for the next, to overcome this limitation.
[o] Developed by the Canadian Interagency Forest Fire Centre (http://www.ciffc.ca/) and led by the Alberta Environment and Sustainable Resource Development (http://esrd.alberta.ca/).
[p] Canadian Wildland Fire Growth Simulation Model (http://www.firegrowthmodel.ca/).
[q] Burn-P3 (Probability, Prediction, and Planning), simulation model for the evaluation of the burn probability in a large fire-prone landscape (http://www.firegrowthmodel.ca/burnp3/overview_e.php).
[r] Version 1.0 released in May of 2002 and used operationally for the first time in the same month to provide fire management decision support for the House River fire, a classic boreal wind-driven fire (248,243 ha), which became the second-largest fire in Alberta since 1961.
[s] E.g., Pandora (to run any number of Prometheus simulations in a batch operation, also included in the Spatial Fire Management System), Pegasus (for fire management staff remotely access Prometheus via the internet), and Burn-P3 (a simulation model used to assess burn probability over a landscape).
[t] Streams can be obtained from observations, forecasts or generated from the time of year and latitude average conditions;
[u] Spatial landscape grids (an optional input) include degree of curing (grass), percent greenup (for mixedwood fuel types), percent conifer (for mixedwood fuel types), percent dead fir, crown base height, and tree height.
[v] Prometheus optionally allows users to input wind direction and wind speed grids; these are usually derived from WindNinja.[at]
[w] Long-range spotting is not natively modeled in Prometheus: it includes a breaching function (for fuel breaks) but does not include spotting over features (usually long range spotting); spotting is implicitly included in the FBP sub-systems of the CFFDRS[x] (i.e., ROS equations) because the FBP System is an empirically based model (Sullivan, 2009a); however, spotting can be added manually.
[x] CFFDRS, Canadian Forest Fire Danger Rating System (http://cwfis.cfs.nrcan.gc.ca/background/summary/fdr).
[y] Spotting and gusting winds are modeled as stochastic processes.
[z] Fuel isolation and conversion.
[aa] Including spatiotemporal smoke emissions estimates.
[ab] Also less operational decisions supported as long-term projections (e.g., climate change);
[ac] FSPro, Geospatial Fire Spread Probability model.
[ad] WFDSS, Wildland Fire Decision Support System.
[ae] WFDSS and FPA, both use LANDFIRE (Landscape Fire and Resource Management Planning Tools).
[af] RAVAR, Rapid Assessment of Values at Risk.
[ag] FSim is the FPA[ai] implementation of FSPro,[ac] included in the Large Fire Module (LFM).
[ah] FlamMap (Finney, 2006), widely used for planning fuel treatments (Ager et al., 2011), is an alternative to FSim because the access to it is not restricted to authorized personal; it can input fire lists that can be generated from statistical models, thereby making it quite advanced and simpler to use; the first paper (Ager et al., 2007) published on wildfire risk from simulation models uses FlamMap; Randig (Ager et al., 2013), the model first used for risk analysis, is a kind of command line version of FlamMap (as Pandora with Prometheus [see s]).
[ai] FPA, Fire Program Analysis.

[aj] Output of the Large Fire Module (LFM) of FPA[ai] where FSim is included.
[ak] http://www.bushfirecrc.com/projects/a41/fire-management-business-model.
[al] http://www.bushfirecrc.com/projects/2-2/enhancement-fire-behaviour-models.
[am] FireDST, Fire Impact and Risk Evaluation Decision Support Tool (http://www.bushfirecrc.com/projects/2-1/risk-assessment-decision-toolbox); development (as prototype) started in 2011, see Cechet et al. (2014).
[an] The state of Victoria began using it operationally for the 2010–2011 fire season;
[ao] PHOENIX Rapidfire was initially one component of a scenario based (non-spatially explicit) bushfire risk management and mitigation model[ak] (developed by the University of Melbourne within the Bushfire CRC, Cooperative Research Centre) to quantify the impact[aw] of several management choices[av] in the resulting fire characteristics.
[ap] Fuel moisture, flammability (heat absorption, combustion), embers (abundance, lofting, burnout, ignition), plume (energy release rate, total heat output, emissions), and suppression (radiation, embers, ease of extinction).
[aq] Spotfires are created by burning embers and occurs when a fire produces firebrands that carried by the wind starts new fires beyond the main fire (Saeedian et al., 2010); this phenomenon happens in most bushfires, especially in eucalypt forests in Australia where large numbers of embers are produced (Tolhurst and Chong, 2009).
[ar] CSIRO southern grassland fire spread model.
[as] McArthur MK5 forest fire behavior model.
[at] WindNinja is a computer program that computes spatially varying wind fields for wildland fire and other applications requiring high resolution wind prediction in complex terrain (http://www.firelab.org/project/windninja).
[au] The Huygens approach used in PHOENIX Rapidfire has been taken from SiroFire.
[av] 54 elements of bushfire management options, grouped in: prevention, preparedness, response, recovery, and fire regime management; these elements cover several management activities including: legislation, planning, public education, firefighter training, equipment development, prescribed burning, fuel management, fire detection, firefighting, use of aircraft, post-fire recovery, environmental rehabilitation and others.
[aw] There are two types of interaction included in the model, the interchangeability and the interdependence between the elements.
[ax] Fuelscape: «A raster-format geospatial characterization of ground, surface and canopy fuel across a landscape, typically consisting of one or more fuel characteristics data layers. For fire behavior modeling, a fuelscape consists of geospatial data layers representing surface fuel model, canopy base height and canopy bulk density. Other geospatial data layers required for geospatial fire modeling include topography characteristics (slope, aspect, elevation) and vegetation characteristics (forest canopy cover and height)», Scott et al. (2013).

that we do not consider, e.g., HFire (Highly Optimized Tolerance Fire Spread Model), a raster-based and computationally efficient model, which was designed to simulate long-term shrubland fire regimes but can be used for single fires (Peterson et al., 2011).

Prometheus and FARSITE are deterministic models with similar functionalities (Dupuy and Alexandrian, 2010). Both adopt the partial differential equations of Richards to propagate each vertex along the fire perimeter but differ in the fuel classification typology, weather-related inputs and fire behavior models used. Prometheus is based on the Canadian Fire Behavior Prediction System (Forestry Canada, 1992) that estimates fire behavior (adjusted for specific fuel types) from fire danger rating codes. FARSITE is part of the suite of U.S. landscape-level fire modeling systems, that also includes FlamMap (Finney, 2006) and the geospatial Fire Spread Probability (FSPro) model (Andrews, 2007), and relies on Rothermel's spread model and associated fuel models. Opperman et al. (2006) compared the two models for wildfires in grass, scrub, and forests, in New Zealand and Australia. Both performed very well. Despite the lack of site-specific fuel models and weather data, local users concluded that the fuel model choice was less important than expected, but having local wind data was imperative because local winds influence the final fire shape. Local users also concluded that the most important criteria in the choice of an application are usability and configuration flexibility.

SiroFire (Coleman and Sullivan, 1996) has been used in Australia as a fire-suppression training tool, using McArthur's fire spread models for grassland and forest as well as Rothermel's model (Sullivan, 2009b). Similarly, fire behavior characteristics in PHOENIX are derived from the CSIRO southern grassland fire spread model and the McArthur MK5 forest fire behavior model (Saeedian et al., 2010). PHOENIX does not adopt state-of-the art fire spread models (e.g., (Cheney et al., 2012)) but incorporates additional models that enhance its dynamic ability, namely for the effects of spotting (also present in FARSITE), wind-slope interactions, fuel accumulation rates, fuel moisture models, self-extinction and fire suppression (Tolhurst and Chong, 2009; Saeedian et al., 2010; Papadopoulos and Pavlidou, 2011; Cechet et al., 2014).

The fire behavior module FSPro (Finney et al., 2011a) uses a computationally efficient form of the FARSITE calculations to simulate 2-D fire growth across the landscape, without suppression. It differs from FARSITE in that it simulates fire growth for thousands of possible weather scenarios, statistically derived from local weather stations data using the latest recorded fire perimeters. FSPro assigns a burn probability to each cell in the landscape by dividing the number of runs of the simulation in which the cell burns by the total number of runs (Calkin et al., 2007). FSim is an implementation of FSPro that simulates thousands of possible fire seasons, varying fuels, weather, suppression and treatments, to estimate burn probabilities and fire size distributions. It uses the minimum travel time fire spread algorithm (similarly to FlamMap), whose extensive application has established that it can be effectively used in heterogeneous landscapes, as is the case of the wildlands in the U.S. (Calkin et al., 2011a; Finney et al., 2011b).

Used for land-management planning (and also for fire research), Burn-P3 (probability, prediction, and planning) is a spatial fire simulation model that uses the Prometheus engine to simulate the ignition and spread of a very large number of fires. The inputs are topography, fuels, weather, and fire ignitions patterns (drawn from a probability density grid with Monte Carlo methods). Fire spread is driven by the weather conditions and fire length is modeled stochastically from user-supplied distributions. Burn-P3's main output is a burn probability map (Parisien et al., 2005, 2010).

Table 1 summarize a set of primary attributes (name, origin, year, primary attributes, inputs, outputs, spread model/mathematical models, deterministic/stochastic, planning context and decisions supported, duration, fires considered, simulation type, type of burn probability, source of variation, and selected references) for the fire behavior, fire spread, and probabilistic fire spread simulators mentioned in this section.

2.2. Fire suppression models

The development of risk-based decision support tools has largely been directed to the management of active fires, especially during initial attack, aiming at preventing fires from escaping and causing damage, since the seminal paper of Fried and Fried (1996). Using some form of simulation, the fire is considered contained when the constructed length of fireline, dependent on the capacity of the firefighting resources employed, equals the fire perimeter determined by its rate of spread; in addition, other factors could be considered, like containment probability, interactions between fireline production and fire growth, fire danger rating, rate of spread, fuel type, or the diversion of resources for structure protection (Thompson and Calkin, 2011). Furthermore, to handle the lack of objective data about some aspects of suppression, expert judgment elicitation has been used by several authors to inform the modeling of the initial attack, e.g. Martell et al. (1999) and Hirsch et al. (2004).

The amount of resources to dispatch to each fire and how to prioritize scarce resources in a multiple fires scenario, are some of the dispatching decisions included in the initial attack and that often must be taken quickly and with limited information (Collins, 2012). The skills, experience, and intuition of the firefighters could be enhanced with this kind of DSS, potentiated by advances in computing power and geospatial data acquisition that enables massive geo-processing, rapid simulations, projection of fire behavior across the landscape and increases the accuracy of fuel conditions (Thompson and Calkin, 2011). Despite these advances, the modeling of escaped large wildfires is still an immature field with significant knowledge gaps since the factors contributing to suppression success remain poorly understood (Finney et al., 2009) and very little is known about the relationship between suppression inputs and fireline construction along the duration of extended attack episodes (Holmes and Calkin, 2013).

2.3. Wildfire management DSS based on economic models

With a limited amount of funding, equipment, and human resources, forest managers must decide the most efficient distribution among alternative fire management options such as prevention (e.g., education, public campaigns), fuel treatments (e.g., prescribed burning, mechanical treatments), pre-suppression (e.g., planning and preparedness, firefighters recruitment and training, maintenance of fuelbreaks and water points), suppression, and restoration measures (Mavsar et al., 2010). Accomplishing that requires the ability to evaluate how wildfires spread with and without suppression and their effects on the monetary value of the destroyed or damaged assets (Mendes, 2010). It further requires being able to assess stand-level prescriptions, including fuel treatments, as wildfire risk is related to stand structure and flammability, and the spatial allocation of prescriptions (e.g., harvest and fuel treatment decisions) in the forested landscape and its impact on the spread and intensity of wildfires.

The evaluation of fire spread and its effects, with and without suppression, requires an extensive amount of information, which is in many cases unavailable, especially concerning the overall social (e.g., ecological values, air pollution) and private (e.g., destroyed assets) costs associated with wildfires. The resulting knowledge uncertainty and substantial gap in the scientific understanding of both short and long-run effects (Brillinger et al., 2009) lead to a lack of resource value measures to guide prioritization across fires and resources at risk (Thompson and Calkin, 2011). Even so, considerable theoretical progress has been achieved (Gorte and Gorte, 1979; González-Cabán, 2007; Mavsar et al., 2013), since the early work of Headley (1916), Lovejoy (1916) and Sparhawk (1925), until the more recent contributions of Donovan and Rideout (2003), including Simard (1976), Mills and Bratten (1982) and Rideout and Omi (1990). Generally, the economic analysis of fire management efficiency makes use of the "cost plus net-value-change" concept, C + NVC (Mavsar et al., 2010).

Starting with FEES, the Fire Economics Evaluation System (Mills and Bratten, 1982; González-Cabán et al., 1986), and even though not always adequately considering the effects on non-market resources (e.g., recreation, flora and fauna, soil, air and water quality, or cultural heritage) (Brillinger et al., 2009), the combination of computer simulation and Geographic Information Systems (GIS) with the economic evaluation of losses and wildfire fighting costs has enabled substantial advances toward the goal of providing *"sufficient data to enable the efficient economic choice of the best combination of fire combat resources per fire type, the integration of cost–benefit analysis, modeling incidence probability as well as the spread of fires lines with and without intervention, per intervention and fire type"* (Mendes, 2010).

Even if this goal has not yet been fully achieved, especially for the management of escaped large wildfires (Finney et al., 2009; Holmes and Calkin, 2013), examples of these systems currently in use include the Canadian "Level of Protection Analysis System", LEOPARDS, the Chilean KITRAL ("fire" in the indigenous Mapuche language), U.S.A.'s "Fire Protection Analysis", FPA, and the Spanish "Sistema Nacional para el Manejo de Incendios Florestales", SINAMI. The latter is a more advanced and updated version of U.S.A.'s "California Fire Economics Simulation Model", FPPS/CFES, operating under the same principles (Mavsar et al., 2013).

2.3.1. LEOPARDS

LEOPARDS (Martell and Boychuk, 1994, 1997) has been in use in Ontario, Canada, since 1995 (McAlpine and Hirsch, 1999a,b). It can model daily fire-suppression activities (Minas et al., 2012), emulating them with inputs that include historical fire weather, fire incidence data, land-use objectives, operational rules, infrastructure and suppression resource information. The system estimates three forms of outputs: physical outcomes (e.g., response time, escaped fires, burnt area), fixed and variable costs, and resource utilization information (McAlpine and Hirsch, 1999a,b; Podur and Wotton, 2010).

LEOPARDS is based on the initial attack model developed by Martell et al. (1983, 1984) and considers temporal queuing conflicts and spatial realities (multiple fire ignitions over a large area or a large number of fires in a small area and in a short time period) of forest fire suppression, situations that often lead to delays in initial attack resulting in more escaped fires (McAlpine and Hirsch, 1999a,b). Podur and Martell (2007) have used it in an attempt to model the more complex problem of the containment of large wildfires (Thompson and Calkin, 2011), wherein the combat is typically opportunistic and meteorologically driven (Martell, 2007; Finney et al., 2009). Currently, with the key improvements focused on the fire behavior simulator and the suppression deployment model, a second version of LEOPARDS is being prepared (Mavsar et al., 2013).

2.3.2. KITRAL

In development since 1993, and in usage after 1996, KITRAL uses simulation models to predict fire behavior including risk, danger, spread rate, wind velocity, flame length and priorities at several time and space scales, using an extensive geographical database (Pedernera and Alvear, 1999). By evaluating different fire management alternatives, for pre-suppression and suppression, KITRAL enables daily (real time) allocation of resources, and strategic planning of activities (Mavsar et al., 2013).

For dispatch, the system locates the areas of reported fires, simulates the spread and the competing needs of simultaneous fires, and calculates the quantities and types of resources that should be sent to efficiently fight each fire (Pedernera and Alvear, 1999).

Tested under real conditions, the results reveal 90% accuracy in forecasts of fires larger than 60 ha, but less reliability in fires affecting less than 2 ha, probably because its grid has a minimum size of 25 m^2. However the system is fast, being capable of simulating a period of twelve hours in three minutes (Soto et al., 2004), and its use may lead to savings in the range of 15–50% of direct losses (Pedernera and Alvear, 1999).

More recently, an optimization model, using integer linear programming, aiming at minimizing the cost of fire control has also been developed and integrated with the system (Musa, 2004; Pedernera et al., 2004).

Soto et al. (2013) have used KITRAL to obtain a global territorial model of economic vulnerability to forest fire (considering direct costs), integrating risk, danger and damage potential, to facilitate the prioritization of suppression activities, even in the wildland urban interface (WUI), where fires are mainly caused by humans.

2.3.3. SINAMI

The research design of the SINAMI model, which includes CARDIN as a calculating tool, was presented in 2004 (Rodríguez y Silva, 2004) and finished in 2006 together with ECONOSINAMI, its module for economic analysis (Rodríguez y Silva, 2007).

SINAMI is a model exclusively intended for strategic fire management planning, using marginal analysis and the economic criterion of C + NVC to determine the most efficient fire management programs and budget levels, and considering a true representation of the historical analysis of the last 10-year average conditions. It enables managers to quantitatively explore the tradeoffs among budget levels and potential losses, and justify budget requests by easily identifying the potential consequences of a budget reduction or relocation. Furthermore, the model provides fire management program compositions and the number of necessary resources (Rodríguez y Silva and González-Cabán, 2010).

The model has continued to evolve, and by 2012 it had already included the impact of wildfires on a variety of tangible and intangible natural resources, such as timber, forage, underbrush, fruits, water, fishing, fauna, recreation, hunting and landscape (Mavsar et al., 2013). In that same year, a pilot project was implemented in two forest areas of Mexico (Rodríguez y Silva, 2010).

SINAMI has been applied to the evaluation of economic losses in Iberian swine production, which depends on privately held pasture lands that may be affected by wildfires, and more broadly, of the direct negative economic impact on rural development (Martínez et al., 2011). In a different application, SINAMI has been used to validate an extension of the thirteen Rothermel fuel models to better represent the Mediterranean ecosystems (Rodríguez y Silva and Molina-Martínez, 2012). The system has also been employed, in an extension of the principle of economic valuation to the concept of economic vulnerability, to provide a cartography of economic vulnerability and value of forest ecosystems, which may provide fundamental inputs for temporal and spatial budget optimization (Rodríguez y Silva et al., 2012).

2.3.4. Fire Program Analysis

In the U.S., in response to the National Fire Plan (Babbitt and Glickman, 2000), a report commissioned by President Clinton after the severe wildfires of 2000, and to the updated Federal Wildland Fire Policy (Interagency Working Group, 2001), the Hubbard report (Hubbard, 2001) proposed that the five federal wildland firefighting agencies should develop and implement a single, common, uniform and performance-based interagency analysis process, including a software application tool to support wildland fire budgeting and planning decisions (Fairbanks et al., 2002).

To evaluate the effectiveness of alternative fire management strategies in time, that system should be objective-driven, performance-based, and should find the most cost-effective program encompassing the full scope of fire management activities (protecting life and property, using fire and other treatments to maintain and restore the health of ecosystems, and reducing hazardous fuels in fire-prone ecosystems), identifying resource needs and sharing opportunities across all jurisdictions. This endeavor was thereafter supported by the Congress, which further required that the resources sharing mechanism should also include non-federal partners (BAH, 2012).

The development of this system, called Fire Program Analysis (FPA), was initiated in 2002 (Rideout and Botti, 2002; Botti et al., 2004) and should have been completed by 2006. However, after the conclusion of the first part of the model in 2004, as the agencies began to use it, officials started raising concerns about the underlying science. As a result, in 2006 the agencies conducted a review, which questioned the basic modeling approach and led to a change from an optimization paradigm (which evaluated all possible combinations and locations of firefighting assets to identify the optimal combination for a given budget level) to a simulation paradigm, incorporating a tradeoff analysis. This change caused a delay of three years in the development of the system, with its expected cost rising from $40 million to close to $54 million (GAO, 2008).

This change on the modeling approach originated an important "knowledge fight" (Buuren and Edelenbos, 2004), i.e., a scientific disagreement featuring intellectual arguments stemming from different approaches to knowledge representation, in both arenas: public (e.g., Fried (2007), wildlandfire.com (2012), Olinger and Gorski (2012)) and academic (e.g., Rideout et al. (2008a,b), Yu et al. (2008), Bruins et al. (2010), Calkin et al. (2011a), Thompson et al. (2012)). The Government Accountability Office (GAO), the audit, evaluation, and investigative arm of Congress, expressed concerns about the simulation-based approach, since it provides considerable discretion to the agencies' decision makers, and in doing so, requires full transparency in those decision processes (GAO, 2008, 2009b,a).

The FPA shares the fire simulation model, FSim, and the Landscape Fire and Resource Management Planning Tools Project, LANDFIRE, with the Wildland Fire Decision Support System (WFDSS) (BAH, 2012; Ryan and Opperman, 2013). These modules are applied independently to each of the 134 Fire Planning Units that cover the continental U.S., and compared with historical data (Finney et al., 2011b), requiring a total simulation time of approximately four months to complete (BAH, 2012).

The required spatial information on fuel structure and topography are provided by LANDFIRE at a 30 m resolution (Finney et al., 2011b). These data are available on-line and are subject to continuous updating (Ryan and Opperman, 2013). However, the full set of simulations only needs to be run after a major LANDFIRE update (BAH, 2012).

After a decade, the FPA development has continued to be characterized by delays and revisions (GAO, 2011a, 2011b). The first results were intended to be used to develop the budget for the fiscal year of 2011 (GAO, 2009a,b), however the scope of usage in that year was limited to supporting the development of the budget request for 2013 (GAO, 2009a,b; BAH, 2012). The system was expected to be fine-tuned, calibrated and fully implemented in 2012 to inform the 2014 fiscal year budget (BAH, 2012), but in its current state, it is not yet suitable for field-level use (BAH, 2012; Thorsen and Hubbard, 2012).

The perception remains, for some stakeholders, that FPA has not achieved the goals set in the Hubbard report, and its current objectives have shifted from the original intent (BAH, 2012). However, FPA promises to achieve some of the key objectives established originally (GAO, 2008, 2009a) and there is no current alternative in the U.S. for the coordination of national fire investments (BAH, 2012).

2.4. Integrating forest and fire management

Recent research has been conducted to develop decision support tools to help integrate forest and fire management planning activities that are currently carried out mostly independently of each other. These tools focus on the support to wildfire prevention planning rather than the management and suppression of active fires. Bettinger (2010) discussed the potential of a wide range of techniques to enhance the integration of forest and wildfire management processes. Borges et al. (2014) presented and discussed the world-wide experience of developing forest management DSS. Packalen et al. (2013) provided a brief overview of this experience. In this section the reader is provided with additional detail about a typical forest management DSS (SADfLOR) to highlight the key functionalities needed to address efficiently and effectively the integration of forest and fire management.

The Portuguese SADfLOR is a DSS with a modular structure that encompasses an information management system, a prescription writer, a model base, a methods base, and a graphical user interface (Borges et al., 2003). Reynolds et al. (2008) provide a detailed description of its architecture. The system was developed with the participation of forest stakeholders ranging from the Forest Service to the forest industry and non-industrial forest owners. Its model base includes growth and yield models for the most important Portuguese species and its methods base includes both exact and heuristic approaches to forest management planning (Garcia-Gonzalo et al., 2013). The system supports strategic and tactical forest management planning and among its applications we may list the development of strategic management plans for the Portuguese pulp and paper industry (Borges and Falcão, 1998), or more recently the Leiria National Forest management plan (Garcia-Gonzalo et al., 2013).

This web-based multiple criteria spatial decision support system has recently been updated with tools to integrate forest and fire management planning. Emphasis was on integrating stand-level fuel treatment scheduling and landscape-level management planning to target socio-economic and ecological objectives while sustaining effective fire prevention levels. Specifically, the SADfLOR model base was updated with models to estimate the probability of stand-level wildfire occurrence according to composition, vertical structure and biometric variables. This is instrumental to understand the effect of stand characteristics on wildfire occurrence probability. The model base was further updated with models to estimate the proportion of trees in a given stand that will die as a consequence of a wildfire event and to understand how stand-level variables impact mortality. These models provide information about the impact of management options on wildfire occurrence probability (Botequim et al., 2013) and on wildfire damage (Marques et al., 2011) in the main forest cover types in Portugal. The new SADfLOR model base thus provides the functionality needed to project conditions and outcomes of interest (e.g., timber flows, carbon stocks) associated with each stand-level prescription under wildfire risk and generate the resulting feasible sets in the criteria space.

The SADfLOR methods base was updated to include management scheduling techniques that might process decision spaces under scenarios of wildfire risk. Specifically, non-linear optimization algorithms (e.g., Hook and Jeeves and populations methods) and stochastic dynamic programming approaches (Ferreira et al., 2012) to stand-level management planning were developed to help managers and landowners: select the sequence of management activities, including fuel treatment and timber harvests, that maximizes soil expectation value for a stand where wildfire risk is related to stand structure and fuel loads; and assess trade-offs between objectives, as well as estimate opportunity costs of non-optimal prescriptions in a wildfire risk context. The methods base was also updated to include a mixed integer programming technique that maximizes the forest value while addressing timber even-flow and landscape wildfire resistance concerns (Ferreira et al., 2014). For this purpose the updated model base was used further to develop a stand-level wildfire resistance index.

2.5. Beyond economic models

Recent developments in near real-time risk-informed decision support (Zimmerman, 2012) for incident management feature a broader scope of concerns, addressing not only economic aspects, but also the likelihood of fire impact on the values at risk.

The Wildland Fire Decision Support System, WFDSS (Calkin et al., 2011b; Noonan-Wright et al., 2011; NFAEB, 2012; Zimmerman, 2012) and the Fire Impact and Risk Evaluation Decision Support Tool, FireDST (Cechet et al., 2014), have been developed as support tools for risk-informed decisions on the management of escaped fires, in the U.S. and Australia respectively.

Developed with the combined effort of several U.S. federal fire management agencies, to reduce redundancy, and in operation since 2009, WFDSS has replaced the former Wildland Fire Situation Analysis (WFSA), Wildland Fire Implementation Plan (WFIP), and Long-Term Incident Planning (LTIP) processes, in a scalable and flexible web based environment (Noonan-Wright et al., 2011; NFAEB, 2012; Zimmerman, 2012). Being a real-time system like Prometheus (Tymstra et al., 2010), Phoenix (Tolhurst et al., 2008) and CARDIN (Martin-Fernández et al., 2002; Rodríguez y Silva, 2004), WFDSS improves the management of escaped large wildfires by supporting integrated risk assessment and the communication between analysts and decision makers (Calkin et al., 2011b).

However, WFDSS differs in a fundamental way. Recognizing the limited understanding of suppression efficacy (Thompson and Calkin, 2011) and the opportunistic nature of suppression effects on large fires (Martell, 2007; Finney et al., 2009), WFDSS does not attempt to model the effectiveness of various alternatives of firefighting resources or suppression tactics, leaving that evaluation to the decision maker in the field. Instead, the system enables usable real-time exposure analysis of the likelihood of fire impact on the values at risk (Calkin et al., 2011b; Thompson and Calkin, 2011).

The two fundamental primary components of WFDSS are the fire behavior module FSPro (Finney et al., 2011a), and the resource impact model RAVAR, Rapid Assessment of Values at Risk (Thompson et al., 2012). Together they provide appropriate fire behavior modeling, overlaid with geospatial identification of human and ecological threatened values (Calkin et al., 2011b; Thompson and Calkin, 2011).

RAVAR identifies the critical infrastructures (private structures, hazardous waste sites, public infrastructure and reserve areas) and the natural and cultural resources (sensitive wildlife habitat, natural resources, recreation zones, and restoration priority areas) within the threatened areas previously identified by FSPro (Thompson and Calkin, 2011; Thompson et al., 2012). This allows WFDSS to support management decisions regarding where and when to perform aggressive suppression or allow the fire to burn, protecting and enhancing ecosystem values (Thompson and Calkin, 2011).

The result of more recent developments in Australia, FireDST is a prototype simulation system based on PHOENIX, that provides an integrated fire risk-assessment framework (Cechet et al., 2014). The intrinsic uncertainty in fire weather (modeled with high-resolution 3-D forecasts), fire spread, exposure to fire and likely impact, are addressed probabilistically through the output of an ensemble of scenarios. By simulating the impacts of fire on community assets, infrastructure and people, FireDST delivers crucial fire-planning information that aids the allocation and prioritization of fire-fighting resources, enabling fast decisions in highly complex situations.

3. From risk assessment to management to governance

The developments described in the previous section have not followed a strictly linear path. This is naturally due in part to the parallel development efforts taking place in different parts of the world, focusing also on applications beyond broad, flexible and integrated forest fire management systems, e.g., emergency evacuation planning (Taylor and Freeman, 2010). Additionally, the decreasing costs of computer storage and computing power are defying well established paradigms, causing a swing in favor of raster-based models, more proficient at dealing with heterogeneous fuels than vector-based models, but requiring geographic data at a high enough resolution to obtain meaningful simulations results – rendering moot the decision between the two (Sullivan, 2009b). Also, as has become apparent in major developments such as the case of FPA, the path between science and practical implementation, involving multiple stakeholders, is often not clear and provides room for "knowledge fights".

Nevertheless, starting from a scientific approach to establish fire spread models, with the early efforts related to the development of BEHAVE (Andrews, 1986) and CARDIN (Millan et al., 1991; Martin-Fernández et al., 2002), we identify in our review a broadening of focus from risk assessment to risk management, and then to risk governance (Fig. 1).

IRGC defines risk governance as the "identification, assessment, management and communication of risks in a broad context", including "the totality of actors, rules, conventions, processes and

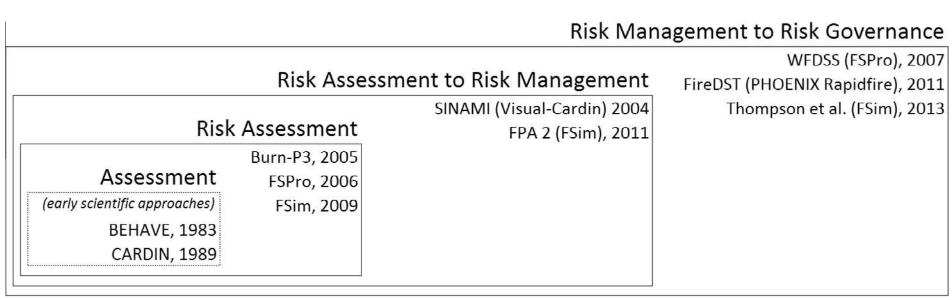

Fig. 1. Conceptual outline of the expanded focus, from risk assessment to management to governance, with examples.

mechanisms concerned with how relevant risk information is collected, analyzed and communicated, and how and by whom management decisions are taken and implemented" (IRGC, 2009). Risk governance's broad picture of risk includes risk management, but also looks at coordination or reconciliation requirements when a variety of actors is present, and in an enhanced way at context to consider "historical and legal background, guiding principles, value systems and perceptions as well as organisational imperatives" (IRGC, 2005). In this context, the role of risk-based decision support is also challenged to be widened and encompass these additional aspects.

Bachmann and Allgöwer (2000) stressed early on the need for a consistent wildfire risk terminology, with a truly modern definition of fire risk, including fire behavior probabilities and fire effects. (Hardy, 2005) noted that at the time there was widespread ambiguity over the term "fire risk", often used to mean only the probability of ignition. Considering the quantitative fire risk model of Finney (2005), incidentally published in the same year as the IRGC Risk Governance Framework (IRGC, 2005), the aim of the early fire spread models cannot be strictly described as being risk assessment, since the basic elements of risk (probability and effects) were largely absent from them. However, the fire behavior "assessment" that they provide became the basis for later true risk assessment systems, such as FSPro and FSim (and the systems using them, WFDSS and FPA, respectively), or any system using a deterministic simulation model together with probabilities (e.g., Burn-P3 with Prometheus, SINAMI with Visual-Cardin, or FireDST with PHOENIX RapidFire).

The progress at that level, together with the development of more effective models capable of taking into account large numbers of alternative scenarios, additionally supported by the availability of increasing computing power, have enabled more sophisticated analyses that could not be performed earlier. Indeed, we can establish a parallel, throughout the last decades, between the increasing comprehensiveness of risk handling and the developments from fire science (§2.1), to economic evaluation (§2.2, §2.3 and §2.4), and then to broader perspectives (§2.5).

3.1. Aligning decision support tools and practitioners

The evolution in these two trajectories, the development of more effective models enabling more sophisticated analyses and the broadening of focus to risk governance, has naturally led to misalignments between decision support tools and the practitioners adopting and implementing them, a fact that has been reflected in lower than expected levels of adoption (Calkin et al., 2011a). This is in fact also perceptible in the broader area of forest management and planning DSSs (Stewart et al., 2013).

On the social and organizational domains, difficulties have in part been linked with low levels of stakeholder engagement in the development and implementation of the DSSs, suggesting the need for improved interactions at the science–policy–practice interface, and the need to expand the absorbing capacity of user communities (Reis and Oliveira, 2007). In the specific case of risk assessment, Borchers (2005) highlights its incompatibility with an unwarranted desire for certainty that managers and policymakers often have, advocating an "embrace" of uncertainty, within a framework that considers the risk "marketplace" while addressing the challenge of "deciding how to decide". Calkin et al. (2011a) also accentuate this organizational perspective, defending the implementation of a continuous improvement process, appropriate incentives, risk management training, and communication with stakeholders who have important socio-political influence. Pasalodos-Tato et al. (2013) add the difficulty in explaining methods for decision support under uncertainty to non-specialists, including difficulties in admitting certain outcomes, unfamiliarity with concepts, and technical difficulties such as: large-scale problems, time-consuming analysis, managing the trade-off between simplicity and accuracy, knowledge about the uncertainties and risks, risk attitude, and interpretation difficulties.

But a focus on risk handling also brings added scientific challenges to the area of fire behavior and effects. Finney (2005) highlights the complexity associated with determining a location's burning probability, related to its dependence on "ignitions occurring off-site and the fuels, topography, weather, and relative fire direction allowing each fire to reach that location", and argues for a common scale to evaluate impacts on the diversity of fire-susceptible values.

Thompson and Calkin (2011) identify multiple sources of uncertainty, ranging from the unpredictability of wildfire behavior, to inaccurate or missing data, limited resource value measures, and an incomplete scientific understanding of ecological response to fire, fire behavior response to treatments, and spatiotemporal dynamics involving disturbance regimes and climate change. Using an uncertainty topology, the authors review decision support approaches for each class of uncertainty. Wildfire effects analysis and value uncertainty are identified as primary challenges to integrated wildfire risk assessment and wildfire management. Minas et al. (2012) also review Operations Research methods and discuss their ability to address some of the major challenges of wildfire management, including complexity, multiple conflicting objectives and uncertainty.

Calkin et al. (2011a) mention the need to address temporal considerations, the challenges that arise from the local scale of resource values, the uncertainty in resource response, aggravated by temporal and spatial concerns, and the social preferences for non-commensurate resources. Yousefpour et al. (2012), referring more broadly to adaptive forest management under climate change, stress the need to handle non-stationary and perhaps even belief-based parameters of stochastic processes to model climate change, and forest growth models that can estimate the production of timber and other resources, incorporate changes in climate, work across multiple scales, and feature a computational complexity that is commensurate with the evaluation of numerous scenarios and alternatives.

Mavsar et al. (2013) review four decision support systems aimed at improving the efficiency of the allocation of resources for fire protection programs, and conclude that in spite of improvements in the theoretical economic model, the advances are still not fully implemented in practice, in particular, the net value change component of the C + NVC model. This is mainly due to lacking knowledge about the impacts of different fire management measures on fire behavior and the resulting damages, and economic impacts, including market and nonmarket goods and services.

Hyde et al. (2013) point out the complexity and multidimensionality of the processes that drive ecosystem changes, and thus the need for tools that account for highly variable effects on multiple values-at-risk and balance competing objectives, and for an analysis framework that works across the range of fire-management activities. Miller and Ager (2013) state that quantitative frameworks are increasingly supporting multiple planning scales, from individual incidents or fuel treatments, to national and higher levels, but also placing a higher importance on the evaluation of multiple resource values, and the consideration of more than one risk factor at a time.

3.2. A holistic, risk-governance perspective

A more holistic view, integrating decision support and risk handling in the context of wildfire management and policymaking, and considering a broader spectrum of concerns and approaches to address the escalating costs and increasing threat to human and ecological values posed by wildfires, has recently been emphasized by Calkin et al. (2011a), Thompson et al. (2013a), and Calkin et al. (2014).

Thompson et al. (2013a) suggest a framework for systematic risk assessment, integrating wildfire simulation and burn probability modeling, expert-based modeling of fire effects and multicriteria analysis addressing multiple sources of value, to be extended to include additional activities in the wildfire management spectrum, such as prefire planning.

Calkin et al. (2011a) point to the need of considering a broad spectrum of approaches, including communication with communities, partnerships with insurers, and engagement with planning boards on zoning and development standards, as has been the case of the "Firewise Communities Program" (www.firewise.org) or the "FireSmart Canada" (www.firesmartcanada.ca) initiatives. A view of fire management as a coupled human-natural system (Moritz et al., 2014; Spies et al., 2014) calls for the search for more than technical solutions alone. As suggested by Busenberg (2004), for this type of systems the use of an adaptive policy design framework (public participatory and learning process) may be useful to tackle uncertainties in wildland fuel reduction prescription, solving some fragilities in models, data and economic assumptions. For these purposes, Marcot et al. (2012) suggest the use of formal decision science procedures and tools in a context of structured decision making, and Calkin et al. (2014) suggest a strategic risk assessment framework to enable the evaluation of the impact of multiple strategic options on various risk factors, describing the advantages of approaching problems with a structured decision process, that allows for a well-structured problem statement and the integration of decisions made at varying spatial scales, at different points in time, by different individuals and organizations in the face of substantial uncertainty and complexity.

This resonates with the adoption of a broader view of risk governance, encompassing risk management in a broader scope, highlighting the coordination efforts among stakeholders to overcome societal challenges. In complex coupled human-environment systems with multi-stakeholder and multi-level decision-making, sound governance approaches are needed to deliver effective risk handling outcomes. In wildfire prone countries, wildfire hazard has been dealt with in ways that have evolved in time from simple risk management routines to integrated fire management frameworks, that address social, economic, cultural and environmental concerns, as well as the complexity and uncertainty in forest fire management systems (Aguilar and Montiel, 2011).

Muller and Yin (2010) have illustrated policy alternatives and their effects using low fidelity scenario prototypes for regional governance of wildfires, stressing the need to account for the multiple and interacting influences over risk that shape voluntary decision making by local authorities and management (Muller and Schulte, 2011). When DSSs are used in a broader framework, with multiple stakeholders who have different perceived values at risk, wildfire hazard mitigation must be regarded as a complex problem, characterized by uncertainty and ambiguity, thus reinforcing the importance of the governance side of risk handling. The scientific and technical support provided by DSSs may be distrusted, as they do not incorporate socio-cultural dimensions. However, if wisely utilized and communicated in the scope of participatory frameworks, DSSs can pave the way to consensus and acceptance of solutions, improving the robustness of management and policymaking.

4. Discussion

Uncertainty arises when physical or biological processes are not fully understood or behavior is not easily describe or predicted, and so, it is unavoidably linked to risk (Morgan and Small, 1992). In the wildfire management decision making process, framed in the scope of coupled human-environment systems, uncertainty about fire behavior, e.g., due to the role of fuel or weather, amplifies ambiguity when social agents or time dependent variables tag along in modeling. Uncertainty challenges both analytical and organizational innovation for participants in risk governance and management process, because complexity and ambiguity change the way the decision making entities or agents perceive the risk or value at risk, thus conditioning their decisions (IRGC, 2009).

In this paper we present the state of the art of DSS available in Australia, Europe and America. The allocation of resources to prevent and suppress fire has gained sophistication with the availability of DSSs to help the national, state and local level managers decide where and how many hectares should be treated, building effective fire-risk reduction programs. The available reliable knowledge and tools can provide useful insights to incident commanders or can illustrate the potential consequences of alternative risk management strategies to managers or policymakers. Despite limitations, they can reliably inform fire management policies and activities such that trade-offs are addressed and resources are rationally allocated and result in effective risk mitigation.

However, despite all the efforts put into risk-based DSS for fire management applications, their adoption by policymakers and managers has been generally feeble, in part because of the perceived inherent uncertainty and ambiguity in the outputs, but probably also because of insufficient stakeholder involvement in DSS conception and development. It must be recalled that decision-making aids enhance but do not replace the experience and intuition of the decision makers (Martell, 1982; Mavsar et al., 2013). A large number of factors must be considered, many of which cannot be measured quantitatively, and fire programs must be placed within their institutional context and constraints. A DSS only quantifies some of the relevant factors in fire management planning, helping to trace complex interactions and relationships, too numerous to be easily followed by one person (Mavsar et al., 2013).

Decision-making aids require a careful implementation process for a successful assimilation in the routine operations of their adopters. In the context of fire management, these implementations are particularly complex, since they involve several stakeholders with very diverse levels and natures of concerns, as evidenced throughout this paper. It is also clear from the fire management DSS literature that these systems must be adapted to local contexts, and that their development is strongly affected by institutional and external pressures (Collins et al., 2013). The success of their implementation depends deeply on opinion leaders, who are affected by the perceptions that they develop about the DSSs. Furthermore, the use of these systems requires certain capabilities, sometimes absent from the operational field.

A framework systematizing the challenges of fire management DSS implementations could substantially benefit the outcomes of these implementations. Drawing from the implementation literature (Rogers, 2003; Greenhalgh et al., 2004), this framework would uncover factors concerning the systems, the context where they are being implemented, and their adopters, and how these factors influence the perceptions, decisions and actions related to the implementation process, which in turn have an impact on the outcome of the implementation. Empirical studies should verify whether the claims from the implementation literature, such as those outlined in the paragraphs below, apply to fire management DSSs.

The implementation literature suggests that the involvement of stakeholders and users in the decisions develops commitment, increases motivation, and helps internalize norms associated to the system (Leonard-Barton, 1988; Rogers, 2003). Furthermore, most of the decisions and the perceptions of adopters are the result of contamination from external influences (Rogers, 2003). Perceptions are mostly related to the personal and global risk of adoption, specifically concerning the impact of the system on the activities of the adopters (Leonard-Barton, 1988; Greenhalgh et al., 2004). Moreover, the compatibility of the system with values, norms, past experiences, and needs of adopters affects their perceptions of the uncertainty related to the system (Rogers, 2003).

The alignment between the capabilities of the adopter and the capabilities required to use the system has also a key influence on perceptions about the system's complexity (Linton, 2002). The lack of that alignment usually leads to initial losses of productivity, which are overcome throughout the implementation project as the system's and the adopter's capabilities, and eventually their structures, are aligned with each other through mutual and dynamic adaptation cycles (Leonard-Barton, 1988). The implementation literature also shows that the flow of the implementation process and specifically its management throughout the adaptation cycles, are strongly influenced by: the characteristics of the technology, such as its complexity, triability, demonstrability, flexibility, and compatibility (Leonard-Barton, 1988; Rogers, 2003; Greenhalgh et al., 2004); the characteristics of the adopter, such as its structure, capabilities, culture, and strategy (Leonard-Barton, 1988; Edmondson et al., 2001; Rogers, 2003; Greenhalgh et al., 2004); the characteristics of the users, such as their perceptions, motivations, and capabilities (Leonard-Barton, 1988; Edmondson et al., 2001; Greenhalgh et al., 2004); and the characteristics of the context of the implementation, such as contamination of outer systems, specific policies, and market pressures (Rogers, 2003; Greenhalgh et al., 2004).

Other important challenges for implementations of fire management DSSs concern their management. Further research should therefore also focus on gathering important managerial insights from fire management DSS implementations that can be useful for later implementations. A main management challenge pointed out by the implementation literature is how to efficiently overcome misalignments between the system and the adopter. Addressing this type of challenge would most likely include systematizing information about the factors that influence a particular implementation project, identifying the misalignments, and promoting the adequate adaptation cycles while carefully managing user perceptions and motivations (Leonard-Barton, 1988; Edmondson et al., 2001; Rogers, 2003).

Additionally, a systematized framework can provide evidence on whether, in the course of fire management DSS implementations, delivery systems and the performance criteria of the adopters adapt to fit the system (Leonard-Barton, 1988), and the targeted users become more skilful, consistent, and committed to its use (Klein and Sorra, 1996). Or whether this transition is a period of strong inertia to change, favouring established routines (Greenhalgh et al., 2004). As several stakeholders are involved, many implementation decisions may have to be orchestrated between them, with dynamics that depend not only on each of them, but also on their mutual alignment (Linton, 2002). The framework should consider how the relations between stakeholders are managed during the implementation of the system. Studies of implementations of fire management DSSs should also explore which managerial practices help enhance the perceptions of the positive impacts, and reduce the negative impacts, and the importance of implementation management complying with the culture and the overall strategy of the multiple stakeholders.

Research on these topics should provide a global perspective about the implementation of fire management DSSs, and allow a systematization of the knowledge about implementations in this particular and complex context.

5. Conclusions

A myriad of interacting social and ecological factors influence the severity of forest fires (Tedim et al., 2013). Thus, we need to understand the non-linear relationships between interconnected physical, biological, and cultural systems to be able to effectively reduce the vulnerability of ecosystems and human societies, through improved and proactive risk governance.

To perform an economic evaluation of the investment in a fire management program, an effective DSS to assist assessing alternatives and making decisions must consider multiple conflicting management options, subject to several sources of uncertainty, and their economic impact in the stream of goods and services disrupted by fire occurrence, establishing the ratio between prevention and suppression expenditures, in face of always present budgetary constraints.

The integration of forest fire risk concerns into forest planning processes is a significant step (Bettinger, 2010). However, more research is needed characterizing the impacts of alternative fire management options on market and nonmarket values at risk, and on the economic losses in goods and services triggered by the fire consequences that they try to mitigate (Thompson and Calkin, 2011; Mavsar et al., 2013). This is particularly important regarding the integration of suppression preparedness planning and fuel management (Minas et al., 2013) considering operational and ecological constrains (Minas et al., 2014).

As research evolves and the available computational power increases, it will be possible to tackle increasingly complex challenges raised by more frequent and destructive fires that threaten lives and homes, in particular in an expanding WUI. Problem structuring methods, system dynamics, simulation, decision analysis, and optimization (Minas et al., 2012), together with qualitative methods such as expert elicitation (e.g., Martell et al. (1999), Hirsch et al. (2004), or Rideout et al. (2008b)), open interviews, questionnaires, and surveys (e.g., Tedim et al. (2013)), can help model the dynamics and advance the understanding of these complex systems, gaining insight into problem structures, and better enabling the exploration of alternative management options. Guidelines on how these techniques may help improve specific aspects of decision-making are provided by Minas et al. (2012), on applications of operations research to wildfire management, and Thompson and Calkin (2011), on the alignment of sources of uncertainty with decision support tools and methodologies. Nevertheless, the performance of even the most accurate DSS will be limited by the quality of the input data. Indeed, the balance between input data errors and models accuracy should inform the need for greater precision since it increases the cost of data acquisition (Sullivan, 2009b). A good understanding of the different sources of uncertainty and their potential impact on losses, should guide the development of a DSS sufficiently easy to implement and use, and parsimonious in the amount of information decision makers need to consider (Pasalodos-Tato et al., 2013).

The implementation of DSSs raises other important challenges that emerge from our literature review, namely the involvement of multiple stakeholders who must be considered in the decision-making processes, the need for adaptation to local contexts (e.g., Opperman et al. (2006)), and the strong influence of external pressures and opinion leaders on adoption decisions and on how users perceive the system. It is vital that these and other implementation challenges are carefully managed. Research aiming at the development of a framework that systematizes knowledge about implementation challenges, and how to efficiently manage them, may significantly benefit such management efforts, and the outcomes of implementation processes.

Risk-based analysis is required for the integration of risk handling and fire management, in order to improve the prioritization of future efforts to mitigate the risks associated with these natural and human caused disturbances. This asks for more research in biophysical and social sciences with a dynamic spatiotemporal perspective, from fire spread and effects models to fuel treatment effectiveness, climate change impacts, and social preferences. Risk assessment should also identify and characterize the importance and weight of uncertainties to improve the management of human and ecological resources at risk, in areas ranging from fuel mapping to how society values those resources (Thompson and Calkin, 2011).

Our review of DSSs in current use stresses the importance of the integration between risk handling and DSS development, to facilitate and improve the quality of decisions under uncertainty, and enable a cohesive fire management in an uncertain environment. It also points out the importance of understanding the institutional constraints of management programs within which forest fire mitigation programs develop, that along with ecological constraints and the need to engage stakeholders, need to be reflected in the usability and flexibility of these systems.

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