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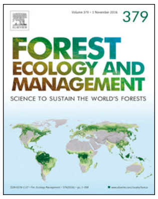

Strategic and tactical planning to improve suppression efforts against large forest fires in the Catalonia region of Spain

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ABSTRACT

The study explores use of the Ecosystem Management Decision Support (EMDS) System to standardize the process of allocating Management Areas for Fire Suppression Support (MASSs) in Catalonia, Spain. MASSs are defined as those areas in the landscape that change fire behavior, reducing the magnitude of the wildfire, and improve significantly fire suppression effectiveness/capacity. Considerations for allocating MASSs include high likelihood of large fires in the vicinity, potential for spread, proximity of the location to valuable resources at risk, proximity to adequate water supply, accessibility by mechanized means, and fuel management opportunities. The combination of accessibility, water supply and fuel management opportunities, when allocating MAASs, provide the minimum requirements to allow fire suppression actions, while improving effectiveness and safety levels. For these purposes, we combine the newest data available, outputs from fire simulators and expert knowledge to define a problem that could be solved using EMDS within a participatory planning framework. To support the fire suppression mission of the firefighting service in Catalonia, this study uses a combination of strategic and tactical solutions, in which the strategic solution identifies high priority locations within the landscape for fire suppression activities, and tactical solutions identify high priority management activities within specific locations.

1. Introduction

Research on methods for preventing the negative impacts of large wildfires continues to be an important area in forest and land-use planning, fire suppression, and civil protection research. The problem is complex as it involves a myriad of aspects that should be taken into account, either from the point of view of predicting the occurrence and behavior of future forest fires, when assessing the value and level of risk of resources at stake, or when identifying the impact that management actions will have on mitigating both the occurrence of large fires and expected losses. Each of these aspects of the problem, individually, and in combination, are affected by several interconnected factors (Millar et al., 2007, Ryan and Opperman, 2013, Herawati et al., 2015).

Fire behavior is influenced by fuel conditions, topography, weather, and fire suppression efforts. Among these factors, fuel conditions and suppression resources can be effectively managed through planning to reduce risks to resources and firefighting personnel. Fuel-management planning traditionally aims to reduce landscape flammability by creating fuel discontinuities in the landscape (Hof et al., 2000; Finney, 2001, Stratton, 2004), or to reduce both the spread of fires and the potential loss of forest resources when combined with forest management (Wei et al., 2008; Gonzalez-Olabarria and Pukkala, 2011). In contrast, planning related to suppression resources aims to allocate those resources to improve their cost-effectiveness (Dimopoulou and Giannikos, 2004, Kirsch and Rideout, 2005, Haight and Fried, 2007). Combined approaches, in which fuel management and fire suppression are integrated into the planning problem, have also been considered (Wei, 2012; Minas et al., 2015), although they are less common. The latter studies rely on the accepted principle that, by modifying fuels across a landscape and therefore controlling the behavior of fire, it will be possible to generate an increased number of opportunities for fire confinement when applying suppression measures.

However, there are various aspects that may limit the effectiveness of planned measures when dealing with large and intense fires, or even the possibility to implement the results of sound research studies in the field. When considering suppression, for example, it is known that under extreme weather conditions, fire behavior often exceeds suppression capabilities (Andrews and Rothermel, 1982), meaning that if a

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fire escapes an initial attack and gathers momentum, suppression efforts have little impact on the occurrence of very large fires, if sufficient fuels are available (San-Miguel-Ayanz et al., 2013, Fernandes et al., 2016a). Furthermore, large fires have several associated factors (either operational, social, psychological, or institutional) that may limit the effectiveness of suppression efforts (Katuwal et al., 2017), as for example the need to protect exposed households in the wildland-urban interface (WUI). Regarding fuel management, even if recognized as the best way to influence fire spread under any condition, it should encompass both a sizeable portion of a landscape under threat and significant reduction of fuel on the treated areas, when dealing with extreme weather conditions (Fernandes et al., 2016b). These requirements often are a limiting factor for implementing effective fuel management in the field. Extensive fuel management requires an economic commitment and negotiation between institutions, landowners, and other social actors. Although the social acceptance of, and even the willingness to pay for, fuel management treatments has been increasing over time (Toman et al., 2014, Varela et al., 2014), especially in areas subject to high fire exposure, this perception does not always translate into the required budgets necessary to cope with much needed fuel reductions. Moreover, in rural landscapes with fragmented ownership, finding the required cooperation between landowners and government agencies to implement large-scale management plans can be a challenging task (Fischer and Charnley, 2012).

The limitations mentioned above are often present in Southern Europe, and definitely in regions such as Catalonia in northeast Spain. There, an increasing number of days with extreme weather conditions, fuel accumulations due to rural abandonment, and a plethora of other accompanying factors have led to an increased number of large fires in recent times (González and Pukkala, 2007). Limited budget and a forest ownership that is mainly private (77%) and fragmented (more than 200,000 owners), with an average size of 30 ha (though many of the properties are much smaller), hamper the application of large-scale prevention plans required to mitigate the negative impacts caused by large fires. As a tool to facilitate the application of management actions in Catalonia, a set of management priority zones have been designed under the umbrella of forest management. One of the most interesting, regarding the mitigation of large fires, is that for the so called *Puntos Estratégicos de Gestión* (PEGs), which are highly delimited areas, which includes a set of infrastructures associated with a pre-defined fire suppression strategy, based on the study of historic large wildfires and their fire spread patterns. On those areas, the Catalan forest administration will implement management actions regardless of ownership once the area is defined as a PEG and a management plan approved. Nowadays, the allocation and delimitation of PEGs is implemented by experts from the GRAF (Group of Support to Forest Actions), a branch of the Catalonian firefighters oriented toward issues related to wildfire. Although the expertise of the GRAF is widely recognized across the EU, the application of mainly expert knowledge to PEG delimitation has certain shortcomings. In particular, the selection of planning criteria and their relative importance are not always as standardized as a regional program might be (Ryan and Opperman, 2013), because delimitation of the PEGs is designed independently for distinct landscapes across Catalonia and implemented by different fire experts.

At the request of the Catalonian government, a project to explore new methodologies to standardize the process of PEGs allocation and resource allocation to PEGs was initiated in 2016. As explained, PEGs consist of a set of infrastructures associated with a pre-defined fire suppression strategy, based on fire spread patterns of past large wildfires and field work. In this sense, Management Areas for Fire Suppression Support (MASSs) were defined as areas that, once adequate fuel management is implemented, could reduce the intensity of fires and support fire suppression maneuvers, according to the requirements of the firefighting service. Therefore, defining the allocation of MASSs, through an open and systematic use of data and decision support systems could be a first step prior to the allocation of PEGs. The specific objective of the project is to define areas that, when properly managed, will have a significant impact on the on-site fire behavior, ease suppression efforts, and subsequently reduce the magnitude of fires. Considerations in the planning process for allocating MASS to landscape units include high likelihood of large fires in the vicinity, potential for spread, proximity of the location to valuable resources at risk, access to adequate water supply, and fuel management opportunities. The combination of accessibility, water supply and fuel management opportunities, in particular, was considered necessary to the allocation of MASSs to ensure that adequate levels of firefighter safety are achieved during fire suppression efforts. Our overall approach to the project employs a combination of strategic planning for spatially allocating MASSs on the landscape, and tactical planning to select priority management actions within individual MASS, for which we used the Ecosystem Management Decision Support (EMDS) system (Reynolds et al., 2003, 2017).

2. Material and methods

2.1. Study area

Based on an existing fire prevention plan, we selected the area of Tivissa – Vandellos – Llaberia – Pradell. The study area covers 76,980 ha, of which 56,287 ha correspond to a core area included in the existing prevention plan, and 20,703 ha correspond to an additional 2-km buffer around the non-coastal limits of the core area (Fig. 1). The area is located in the province of Tarragona, a region of Catalonia in northeast Spain. The area is considered to be at high risk of fire due to a history of recurrent large fires, abrupt topography that goes from sea level to 921 m.a.s.l, and the presence of towns and individual households embedded within the landscape. Forested lands in the study area occupy 27,187 ha, and are mainly dominated by *Pinus halepensis* forests (81.68%), and *Quercus ilex* (14.43%). An additional 23,481 ha are covered by shrublands, 17,700 ha to fruit and olive trees plantations, 3382 ha to small shape agricultural cultures, while the remaining areas correspond to urban land, roads and paths, rock lands or any other land use without vegetation cover. The study area encompasses 37,392 land-cover units (LCUs) as defined by the Land Cover Map of Catalonia (MCSC-4 2009, http://www.creaf.uab.es/mcsc/usa/index.htm), which were used as the GIS input layer for our analysis and results. LCUs have a mean patch size of 20 ha, but patch size is highly variable, ranging from less than 100 m^2 to over 1000 ha.

2.2. Conceptual design of the planning problem

The first objective of the study was to prioritize LCUs within the study area (1) based on conditions that support the spread of large wildfires, (2) that have valuable resources nearby, (3) and that have good access to water points and escape routes (paths at least 3 m wide). In the context of spatial decision support, this phase of the analysis can be viewed as strategic prioritization insofar as we are attempting to spatially allocate MASSs, considering which are the high priority landscape units (Reynolds et al., 2017), given the above three criteria. The second objective, given the identification of MASSs under objective 1, was to identify which fuel treatments would be the most effective within high priority MASSs with respect to limiting potential fire intensity and allowing firefighters to work more efficiently and more safely during suppression activities. In the sense of Reynolds et al. (2017), objective 2 is concerned with tactical prioritization, in which the focus shifts from the question of *where* (objective 1) to the question of *which* management activities (e.g., alternative types of fuel treatment) are the highest priority, given the spatial context of any particular MASS.

In order to meet the above objectives for strategic and tactical planning, our analysis process implements the following general steps (Fig. 2):

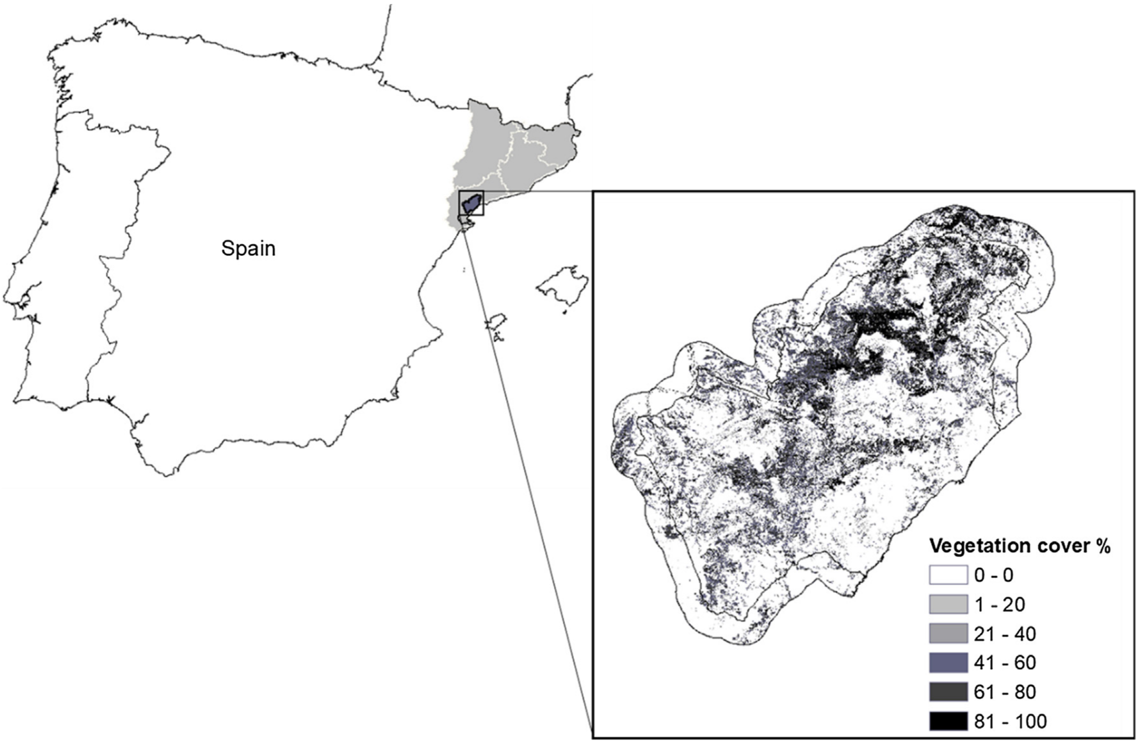


Fig. 1. Location of the study area within the Catalan province of northeast Spain.

1. Assemble the necessary existing spatial and non-spatial data;
2. Derive new spatial variables as needed from the assembled data; for example, fuel characteristics derived from vegetation information (combining spatial data with non-spatial models), or fire behavior variables (by running spatially explicit fire-spread simulators under a set of selected fire weather conditions);
3. Design and implement a logic model for fire potential as a formal specification for interpreting and synthesizing data that determine fire potential (e.g., those conditions that allow a large fire to continue spreading, being a combination of fire hazard (as in Hardy, 2005), fire behavior, and extensive continuous accumulations of heavy loads of fuels);
4. Design and implement a multi-criteria decision model (MCDM) for strategic allocation of MASSs, considering both the logic-based evidence for fire potential (from step 3) and logistical factors important to fire managers and fighters such as unit proximity to high value resources, access to adequate water supply for firefighting, and proximity of escape routes.
5. Design and implement a MCDM for tactical decisions concerning selection of best fuel management alternatives in specific LCUs.
6. Finally, all data from steps 1 and 2, and models from steps 3 to 5 are assembled and run in the Ecosystem Management Decision Support (EMDS) system (Reynolds et al., 2003).

In steps 3 to 5 above, we refer to the design and implementation of the various models employed in our analysis. In the design phase, the structures of logic and decision models were informally sketched in conceptual models. In the implementation phase, the logic model for

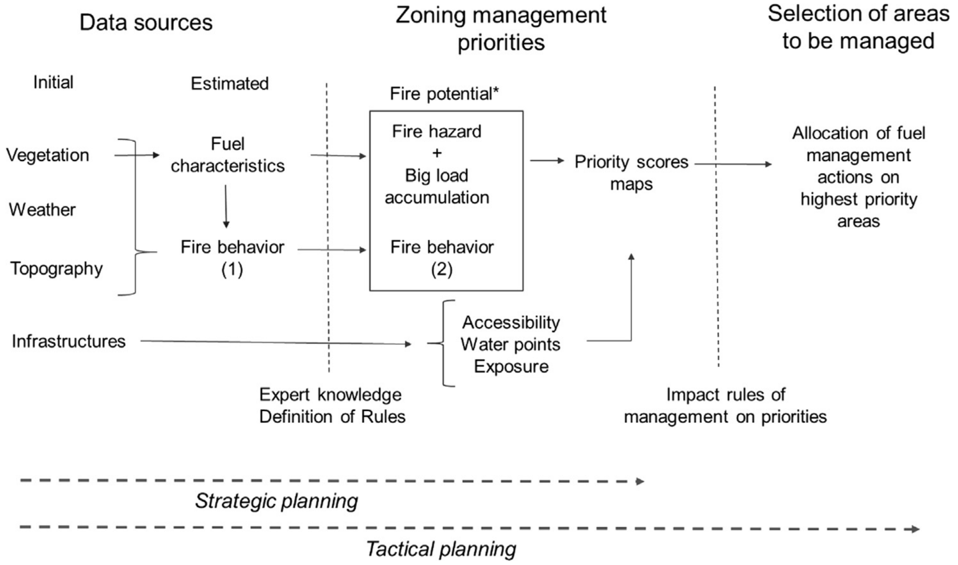


Fig. 2. Schematic of analytic steps for strategic allocation of MASSs and tactical planning to improve suppression effectiveness.

Table 1
Data sources.

Variable	Origin	Format	Unit
Sp. Composition	MCSC 4[a]	vector	Sp name
Digital terrain model (MDT)	ICGC[b]	20-m raster	Meters, m
Accessibility	GRAF[c]	Polyline	Presence and wide (m)
Waterpoints	GRAF	Point	Presence and capacity (m^3)
Households	ICGC	Polyline	Presence
Forest canopy cover (Fcc)	LiDARCAT[d]	20-m raster	%
Mean tree height (Ht)	LiDARCAT	20-m raster	m
Basal Area (BA)	LiDARCAT	20-m raster	m^2/ha
Tree mean diameter (dm)	LiDARCAT	20-m raster	cm
Canopy bulk density (CBD)	Estimated[e]	20-m raster	Kg/m^3
Canopy base height (CBH)	Estimated	20-m raster	m
Fuel models[f]	Estimated[f]	20-m raster	Categorical
Flame length (Fl)[g]	Simulated[g]	20-m raster	m
Fire intensity (Fi)[g]	simulated	20-m raster	kW/m
Rate of spread (ROS)[g]	simulated	20-m raster	m/s
Historic fires	GRAF	vector	Presence and year

[a] Land Cover Map of Catalonia, (http://territori.gencat.cat/es/detalls/Article/Mapes_variables_biofisiques_arbrat).

[b] Cartographic and Geological Institute of Catalonia.

[c] Internal data of wildland firefighter (Group of Support to Forest Actions).

[d] Forest variables derived from airborne LiDAR (http://territori.gencat.cat/es/detalls/Article/Mapes_variables_biofisiques_arbrat).

[e] Estimated using statistical models (Coll et al., 2011; Ruiz-Peinado et al., 2011, 2012) and allometric relations from the Spanish national forest inventory (MAGRAMA, 2017).

[f] Fuel models (Anderson, 1982) adjusted using rules according to Appendix B.

[g] Calculated by Wildfire Analyst (Ramírez et al., 2011).

fire potential was implemented in the NetWeaver Developer software from Rules of Thumb, Inc. (North East, PA, USA), while the decision models were implemented in the MCDM software, Criterium DecisionPlus from InfoHarvest (Seattle, WA, USA). Steps 1–6 involved the participation of an expert group composed of specialists from the GRAF and other experts on forest fire prevention to design the logic models for fire potential and MCDMs for strategical and tactical allocation of the MASSs.

Steps 1 to 6 above are explained in greater detail in the following sections.

2.3. Data sources

From the study area, we gathered spatially explicit data on vegetation status, topography, and presence of infrastructure and households (Table 1). Some initial data on vegetation status, namely tree and bush composition (MCSC 4), a digital terrain model, and information on tree diameter, tree height, forest canopy cover, basal area were derived from LiDAR data (http://territori.gencat.cat/es/detalls/Article/Mapes_variables_biofisiques_arbrat), and were used to estimate additional variables such as bush cover, canopy base height, and canopy bulk density. Those new variables were estimated by applying existing models (Coll et al., 2011; Ruiz-Peinado et al., 2011, 2012) and allometric relations generated from the 4th Spanish national forest inventory (MAGRAMA, 2017) from Management Areas for Fire Suppression Support (MASSs) All initial and estimated information, including a fuel model map (see Appendix B for rules to adjust the standard Anderson, 1982 fuel models) was converted into a landscape (.LCP) file (Finney, 2006), that was subsequently used to simulate fires and calculate fire behavior variables.

Fire simulations were implemented using the Wildfire Analyst™ (Ramírez et al., 2011). Different simulations were generated according

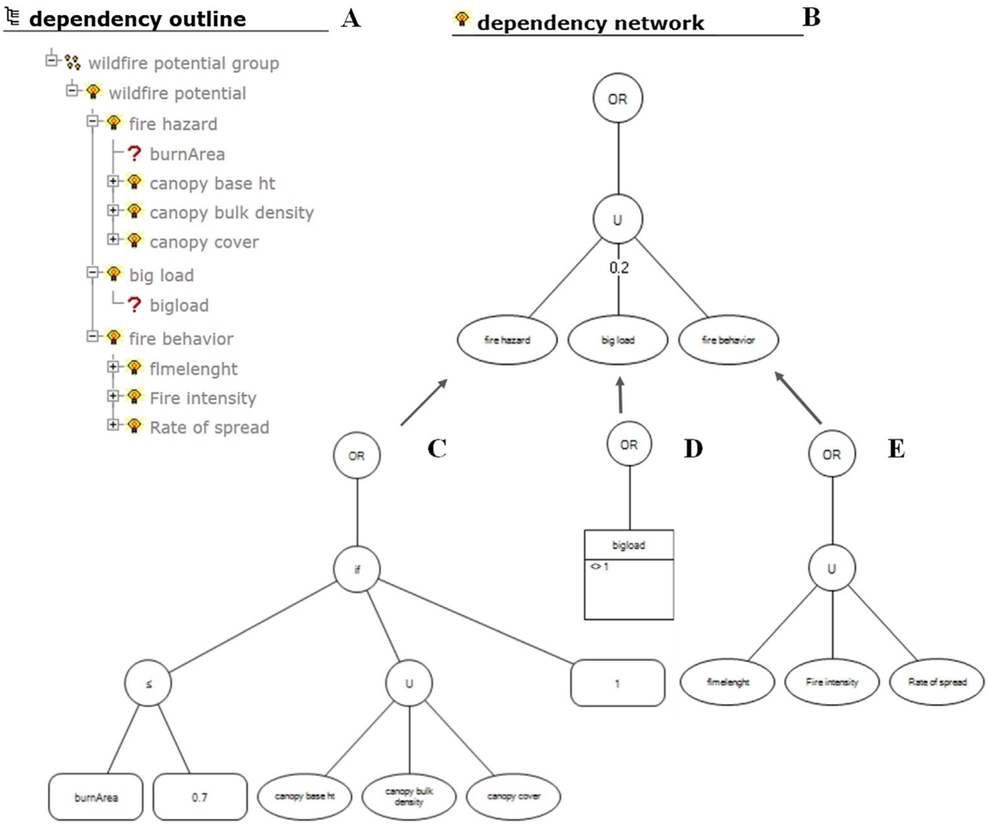


Fig. 3. NetWeaver logic model for fire potential. A, simple outline view of model structure; and the logic specifications for B, fire potential; C, fire hazard; D, big load; and E, fire behavior. Complete documentation for the fire potential model (Fig. 3) is provided in HTML in the supplementary material accompanying this paper.

to three weather scenarios, representing those weather conditions that drive the occurrence of large fires, being those conditions defined by winds of *mistral*, *marinada* and *south*. Weather files for each scenario were obtained from the automatic climatic station of Perello (UTM: 307601N 4527387E), identifying three days of extreme conditions for each scenario (for *mistral* the 10/04/2005; for *marinada* the 14/08/2003; and for *south* the 13/08/2000: see Appendices C–E for the fire weather files). Based on these weather files, and the previously generated LCP file, we simulated multiple fires using 122 ignitions per scenario, being those ignitions systematically allocated following a 2.5 × 2.5 km grid, and letting fires spread until self-extinguished or they had reached a simulation period of 72 h. From the simulations, we computed flame length, fire intensity, and rate of spread for any point affected by fire for inclusion in our analysis.

2.4. Logic-based landscape assessment of wildfire potential

We used the logic-modeling software, NetWeaver Developer (Miller and Saunders, 2002), to assess wildfire potential in LCUs of the study area (Fig. 3). In our model, fire potential depends on fire hazard, fire behavior, and big load (e.g., an unusual accumulation of fuels over a continuous area). Fig. 3a shows a simple hierarchical view of the model that omits details of structure and logic operators, while Fig. 3b–e show more detailed representations of the four major logic networks that make up the model. The four networks (fire potential, fire hazard, big load, and fire behavior) each test the null proposition that observed conditions related to their respective topics do not contribute to fire potential. Thus, the logic for fire potential tests for the condition that fire potential is low, and the three networks on which it depends (fire hazard, big load, and fire behavior) similarly test that hazard, fuel load, and behavior do not contribute to a conclusion of high fire potential.

We illustrate the concept of logical dependency for fire potential (Fig. 3b). The logic topic, fire potential, is represented by a logic network whose specification states that evidence for fire potential is low to the degree that evidence for its logical premises (fire hazard, big load, and fire behavior) are low. The U(nion) operator (Fig. 3b) further specifies that the evidence provided by the three premises of fire potential incrementally contribute to the conclusion about (or evidence for) fire potential. Two additional ways in which to understand the meaning of the U operator are that the lines of evidence under U are additive or compensatory. An alternative operator, AND (not used in the present model), treats the lines of evidence as limiting factors. The logic specification for fire behavior Fig. 3e is analogous.

The logic for fire hazard (Fig. 3c) is an example of conditional logic, in which the evaluation of fire hazard depends on the variable burnArea. In particular, if the proportion of burnArea, during the past 10 years, in an LCU ≤ 0.70, then the network evaluates the three topics (canopy base ht, canopy bulk density, and canopy cover) under the U operator, otherwise (if burnArea > 0.70) fire hazard evaluates to 1 (e.g., there is too little land left unburned in the LCU to contribute to fire hazard). The scale of evidence in NetWeaver ranges over the interval $[-1, 1]$, where a value of -1 indicates no support for the proposition, and a value of 1 indicates full support for the proposition.

NetWeaver models are structurally recursive in the sense that they are composed of networks of networks. However, all logic pathways in a NetWeaver model eventually terminate in elementary networks that only evaluate data. In our model for fire potential (Fig. 3), the networks canopy base height, canopy bulk density, canopy cover, big load, flame length, fire intensity, and rate of spread are all elementary networks. Evidence values are initially generated at the level of elementary networks, most generally by means of fuzzy membership functions that translate observed values of model inputs into measures of strength of evidence. Evidence values originating at this level are propagated upward through the logic operators of networks successively higher in the network structure. Parameters used to define fuzzy membership functions in all elementary networks of our model (Fig. 3) are defined in Table 2.

Table 2
Parameters defining the fuzzy model that interprets different sources of data in terms of a unique statement. The values defining the evidence accomplishment originated from literature (Hessburg et al., 2010; Pique et al., 2011), and expert readjustment.

Metric influencing the low fire potential	Parameter indicating level of evidence accomplishment	
	No evidence	Full evidence
Patch proportion with canopy base height < 3 m	0.5	0.2
Patch proportion with canopy bulk density > 0.15 kg/m^3	0.79	0.29
Patch proportion with canopy cover $> 70\%$	0.6	0.3
Patch proportion with $\geq 70\%$ area burned in previous 10 yrs	0	1
Big load (continuous areas > 100 ha) with (CBD > 0.15 kg/m^3)	1	0
Patch proportion with flame length > 3 m	0.5	0.1
Patch proportion with fire intensity > 350 kW/m	0.5	0.1
Patch proportion with rate of spread > 1.2 km/h	0.5	0.1

2.5. Strategic priorities for fuel management

The goal of the strategic prioritization was to identify LCUs that are a high priority for allocation to MASSs, considering both NetWeaver outputs from the evaluation of fire potential (Fig. 3), and additional logistical considerations that are important to fire managers. The additional logistical considerations included accessibility (distance to roads from a potential PEG), availability of waterpoints, and proximity of the potential MASSs to households (Fig. 4). For this purpose, EMDS uses the MCDM engine of Criterium DecisionPlus (CDP) to evaluate strategic priorities (Murphy, 2014), using a combination of the Analytic Hierarchy Process (AHP) to derive weights on decision criteria (Saaty, 1992), and the Simple Multi-Attribute Rating Technique (SMART) to translate observations on model attributes into normalized [0, 1] utility scores (Kamenetzky, 1982). The relative importance of each criterion in the decision model was agreed by consensus among a group of experts (2 senior firefighters and 2 forest researchers) in order to derive criterion weights (Fig. 4). Each of the attributes used as inputs to the model was normalized into the [0, 1] utility scale using ranges on utility functions determined by the group of experts (Table 3). According to the structure of the strategic decision model, those areas with a high fire potential (accomplishment of the evidence close to -1), accessible by firefighters, where water points can be found nearby, and close to areas of high value, are the ones that should be prioritized for management actions.

Attributes for secondary decision criteria under the criterion for fire potential are interpretations generated by the NetWeaver logic model for fire potential. Additional criteria in the model are logistical factors important to fire managers. Numbers preceding names of criteria are the calculated weights determined by fire managers, and are derived from expert input on the relative importance of criteria. In EMDS applications, the alternative level of the model only requires designation of a single alternative, which EMDS uses as a placeholder to link spatial database records to the model.

2.6. Tactical priorities for management actions within MASSs

After a strategic priority score was obtained for each of the 37,392 LCUs, the 1000 patches with the highest strategic priority were selected for a subsequent tactical analysis to identify the highest priority

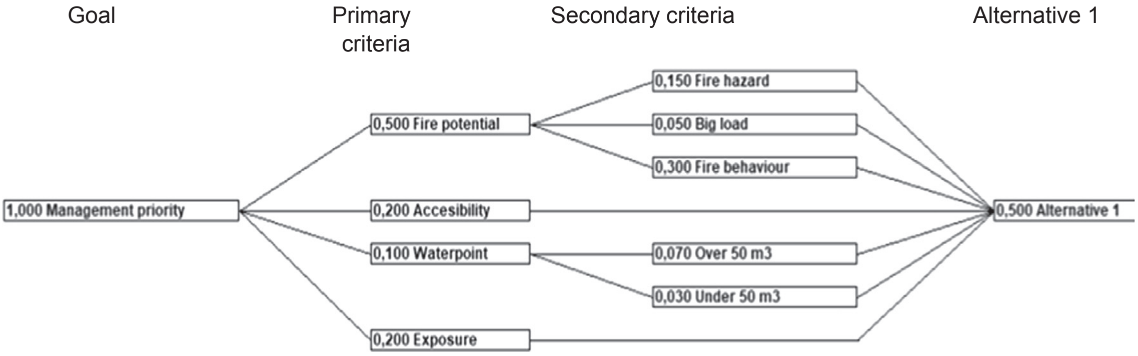


Fig. 4. Strategic decision model for prioritizing allocation of MASSs to LCUs.

Table 3
Parameters defining utility functions for criteria defining management priority.

Criteria (units)	Worst case (utility = 0)	Best case (utility = 1)
Fire hazard (NetWeaver)	1	−1
Big load (NetWeaver)	1	−1
Fire behavior (NetWeaver)	1	−1
Accessibility (distance to road/path (m))	≥800	0
Waterpoints > 50 m^3 (distance (m))	≥1200	0
Waterpoints < 50 m^3 (distance (m))	≥1200	0
Exposure (distance to households (m))	≥8950	0

management actions within each LCP.

Recall from the section, *Conceptual design of the planning problem*, that strategic analyses were run independently for each fire simulation scenario (*mistral, marinada, south*), because the outcomes of those scenarios were expected to be quite different with respect to fire behavior, taking into account the weather conditions used to run the fire spread simulator. Consequently, the tactical analysis was run independently for each fire simulation scenario.

The tactical analysis aimed at selecting the best single (or combined) management alternative(s) that most reduced the negative impact of stressors on hazardous fire conditions. Reduction of fire hazard was selected as the overall goal in tactical analyses, because it can be directly influenced by fuel management operations and easily estimated afterwards (Fig. 5). Model weights in our tactical model were developed by the same group of experts that determined criteria weights for the strategic analysis.

The management actions in the tactical model (Fig. 5) are described in terms of objectives. Actual actions intended to meet these objectives would include more specific management actions such as, thinning, pruning, or prescribed burning. Additionally, a reduction of one of the stressors through any management action may have repercussions on other stressors. For example, a heavy thinning will reduce both canopy cover and canopy bulk density at the patch level, and canopy base height would be increased by a low thinning. Overall, the tactical analyses provide insights into how specific objectives should be attained on the MASSs to ensure further fire safety, by reducing the fire hazard.

2.7. EMDS as a decision support system for strategic and tactical planning

The Ecosystem Management Decision Support (EMDS) system (Reynolds et al., 2003, 2014) was selected as the analytical framework of the planning problem. The system has provided support for decision making processes for a wide variety of spatial planning problems since 1997, including evaluation of danger and treatment recommendations for severe wildfire (Hessburg et al., 2007). EMDS integrates logic and decision engines into a GIS environment, in this case the ArcGIS® 10× geographic information system (GIS, Environmental Systems Research Institute, Redlands, CA). The NetWeaver logic engine (Rules of Thumb, Inc., North East, PA) evaluates the state of an ecosystem, based on logic-based specifications, through the combination of an intuitive graphical user interface, object-based logic networks of propositions, and fuzzy logic, either on the basis of individual or combined factors (Reynolds, 2001, Miller and Saunders, 2002). Criterium DecisionPlus® (CDP, InfoHarvest, Seattle, WA) provides the decision engine, that by implementing analytical hierarchy process (AHP) (Saaty, 1992, 1994), defines scores of management priority for strategic planning according to defined criteria, weights and utilities. Additionally, the latest version of EMDS 5.5 provides decision support for the effectiveness of tactical actions by defining goals, threats and stressors, assigning weights to different management actions according to the relative importance of the threats and stressors associated with the action, and by setting the expected impact of each management action in addressing a stressor (Reynolds et al. 2017).

Information generated by NetWeaver consists of maps with the level of evidence [−1, 1], as an evaluation of the state of the landscape. For example, LCUs with a small proportion of area occupied by dense and continuous vegetation, and especially when the vegetation corresponds to large trees where the insertion of the lower branches is far from the ground, or at least on two of the three characteristics, will have a relatively high evidence level, regarding fire hazard, and therefore there is a good chance that they will not have a large impact in terms of facilitating the spread of large and intense fires. Working similarly at any level of the logic models, the information provided by NetWeaver helps to handle interactions between diverse sources of data, and simplify the decision models in subsequent steps by harmonizing the

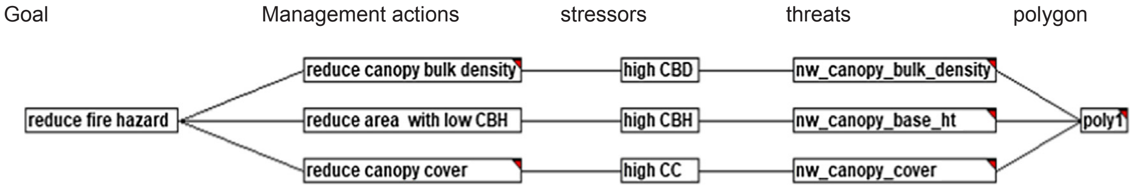


Fig. 5. Tactical decision model to prioritize management actions with respect to reducing fire hazard. Model weights on management actions developed by the expert group were 0.4, 0.2, and 0.4 for reducing canopy bulk density (CBD), canopy base height (CBH), canopy cover (Fcc), respectively.

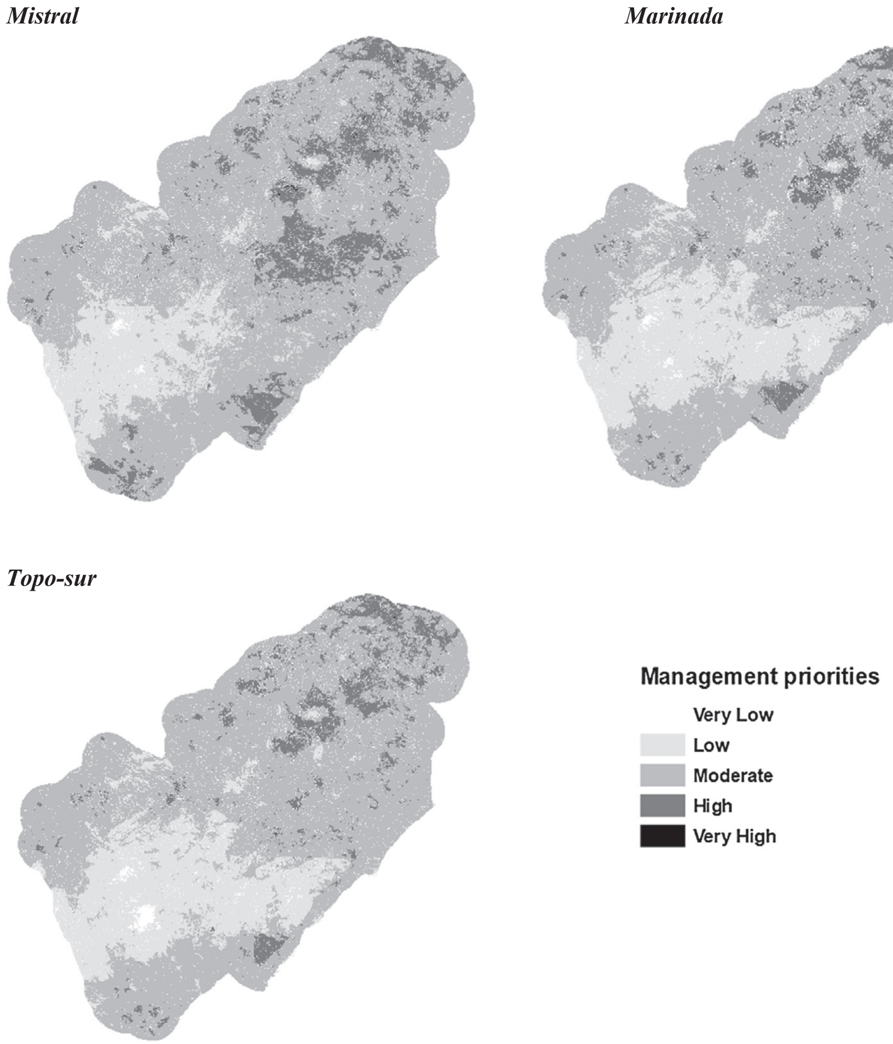


Fig. 6. Distribution of management priorities across the study area.

information (Reynolds et al., 2017). Similarly, the strategic and tactical results generated through the MCDMs are converted to maps in which the scores for strategic and tactical alternatives are allocated. In this way, the user can visually identify which areas of the study landscape offer the best combination of factors (regarding fire potential, exposure, and infrastructures) to be susceptible of fuel management, and on certain places (1000 LCUs, in our case) the more adequate management action.

3. Results

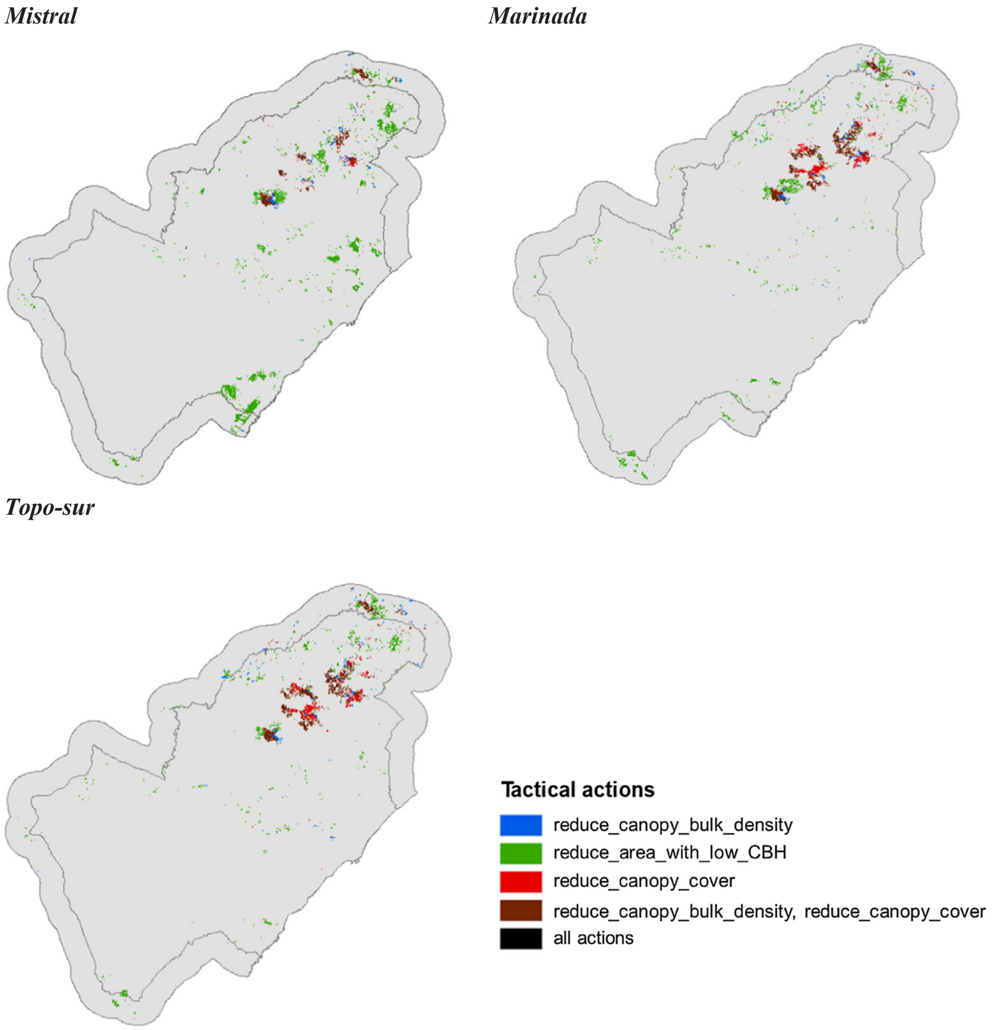
3.1. Strategic management priorities for MASSs allocation

Based on the strategic decision model for prioritizing PEGs allocation (Fig. 4) we obtained scores for all the land cover units across our landscape (Fig. 6). The spatial distribution showed clear similarities for all fire simulation scenarios, because several criteria had the same input values (fire hazard, big load, accessibility, waterpoints, exposure), while differing on the values of those factors defining fire behavior (Appendix - evidence NetWeaver outputs). The more extreme fire weather conditions of the Mistral scenario resulted in a total burned area of 44,183 ha (accumulated from all fires generated through the 122 ignitions) with average and maximum values on the recorded fire behavior variables (Fi, Fl, ROS) that approximately doubled those ones obtained for the *marinada* and *topo-sur* scenarios. On the other hand, fire simulations under the *marinada* and *topo-sur* scenarios yielded similar results either on fire behavior and accumulated burned area, 37,692 and 37,863 ha respectively. This variation in fire behavior coming from the *mistral* scenario, and the subsequent lower fire behavior evidence (more intense and fast spreading fires) across our landscape, should explain both the occurrence of larger areas with higher management priorities for this scenario (Fig. 6, Table 4).

Those areas with higher priority scores, including those with a very

Table 4
Extent of the management priority classes, where the classes are divided in 0.2 score intervals, being very high for those patches with values from 1 to 0.8, and very low those ones with values lower than 0.2.

		Priority				
		Very high	High	Medium	Low	Very Low
Mistral	N	22	5300	27,602	4298	170
	Mean area (ha)	0.85	1.94	1.91	2.64	1.14
	Total area (ha)	18.8	10,286	52,776	11,338	193.6
Marinada	N	9	4410	27,916	4826	231
	Mean area	0.58	14.99	1.89	4.09	1.25
	Total area	5.2	6595.4	52,798	14,924	289.4
Topo-sur	N	8	4265	28,015	4852	252
	Mean area	0.54	1.46	1.8	3.58	1.99
	Total area	4.3	6212.8	50,534	17,358	502.5


Mistral

Marinada

Topo-sur

Fig. 7. Distribution of the recommended management actions across the study area.

high management priority and some of the top scored from the high priority class, should be considered as potential allocations for MASSs, while identifying which fuel management action should be considered to improve working conditions for firefighters.

4. Tactical priorities for fuel management actions

The top 1000 scored patches per fire scenario were selected for implementing a tactical analysis on the most effective management actions required to reduce hazardous conditions that hamper firefighter's safety and limit the efficiency of their work. The potential management actions and the impact on reducing fire hazard were defined on the tactical decision model (Fig. 5). As expected, the allocation of the selected 1000 patches was fairly similar in the case of the *marinada* and *topo-sur* fire scenarios, while the *mistral* scenario demonstrated a more scattered spatial pattern (Fig. 7). Still, aggregation of patches on the central-northern part of the landscape was consistent for all scenarios, where both fire hazard and big load conditions favored occurrence of large fires. In all cases, the preferred management action was a reduction in the area with low canopy base height (Table 5), even if for *topo-sur* conditions and to some extent for *marinada*, reducing both forest cover and canopy bulk density on a combined management action was recommended on a similar area, but concentrated on fewer but larger patches.

Table 5
Extent of the recommended management actions, where > CBH corresponds to an increase in canopy base height, < CBD is a reduction of canopy bulk density reduction, < FCC implies a reduction on forest canopy cover, and < CBD; < FCC or < CBD; > CBH; < FCC are combinations of the above.

		Management actions				
		> CBH	< CBD	< FCC	< CBD; < FCC	< CBD; > CBH; < FCC
Mistral	N	691	112	59	137	1
	Mean area (ha)	1.89	1.12	0.86	2.08	0.19
	Total area (ha)	1308.3	125.2	50.8	284.9	0.2
Marinada	N	544	157	100	199	
	Mean area	1.39	0.85	2.54	2.76	
	Total area	758.2	133.1	254.5	549.2	
Topo-sur	N	477	182	119	226	
	Mean area	1.22	9.93	2.58	2.58	
	Total area	583.3	169.2	297.2	582.5	

5. Discussion

This study aims at improving suppression effectiveness through fuel management activities. The approach developed prioritizes LCUs areas and the allocation of MASSs using a transparent methodology by the combination of state-of-the-art research knowledge with expert knowledge and transparent participatory planning methods. The nature of our problem differs from most studies dealing with planning fire impact mitigation. Our approach considers fuel management, by prioritizing its allocation and by defining management actions to be implemented, as the core of the planning problem, but it does not reflect the typical approaches of previous studies. The reasons being, first, that it does not explicitly aim to reduce the potential fire spread across the landscape (Finney, 2001, Loehle, 2004, Calkin et al., 2005, Finney et al., 2007), second, that the management actions defined in our results are not regarded as having a tangible impact on decreasing the losses of valuable resources (Bettinger, 2009, Kim et al., 2009, Gonzalez-Olabarria and Pukkala, 2011), and finally, that even the strategic assessment of management priorities does not include a deep evaluation of fire risk across the landscape (Thompson et al., 2016). Similarly, although an improvement in the effectiveness of suppression efforts is an objective on our planning problem, the study does not deal with the goals often raised on research studies dealing with such issue, as for example by evaluating cost-efficiency of suppression resources (Mendes, 2010), allocating their deployment to improve their impact on fires (Dimopoulou and Giannikos, 2004) or by assessing fire suppression priorities (y Silva et al., 2014). We do not consider factors explaining fire suppression preparedness, but do consider some of the factors influencing fire response to suppression activities (Duff and Tolhurst, 2015). However, we did not evaluate the extent to which suppression efforts will be more effective or of the extent to which firefighter safety is achieved through our suggested management actions, even if improving these elements is the main driver for our study.

Our study aims at improving suppression effectiveness through fuel management activities, but it hardly can be put in context with previous research in terms of aims and results. Yet, our study aims at reducing the common lack of acceptance that often appears when results of research studies are to be implemented in the field (Riddick et al., 2017). Combining new research advances and tools, with the knowledge, requirements and opinions of final users, to solve a specific real world problem, is the basis for the acceptance of the problem solution. With the focus on developing an approach that may be accepted by decision makers, we combined new tools and end user knowledge and demands.

First, we applied state of the art methods in fuel modeling based on airborne LiDAR data to generate the required inputs for fire simulation at a fine scale (Gonzalez-Olabarria et al., 2012), including new allometric relations and classification algorithms, but also with readjustments coming from experts to solve potential discrepancies. An example of this readjustment was the identification of potential changes over time on the landscape between the time when LiDAR data was captured and the present, due to sudden events such as fires, and then generating rules to reflect such changes. Another example of combining advances in data generation and end user requirements and expertise is the use of Wildfire Analyst™ (Ramírez et al., 2011) to assess fire behaviour. Wildfire Analyst™ is a new, but well tested, fire simulator, developed under a continuous process of improvement (Monedero et al., 2017), and which was recommended by the GRAF experts. This system allowed us to generate and record information from multiple individual fires across the landscape. Combining the newly generated fuel data from LiDAR, a fire simulator recommended by end users, and a set of weather scenarios also defined by experts, not only produced innovative and technically sound results on fire hazard and fire behavior, but maximized the acceptance of these results by end users. Following the same principle, we divided and later combined those factors influencing fire potential in three main components, fire hazard, fire behavior and big load. Although those three components are not fully independent, each provides a unique aspect of fire potential that requires a specific interpretation. Fire hazard, as defined by Hardy (2005) "expresses the potential fire behavior for a fuel type, regardless of the fuel type's weather-influenced fuel moisture content". When included in our logic and decision models, fire hazard highlights the influence of fuel characteristics on fire potential, being at the same time the fire potential component that can be modified through localized fuel and forest management actions. Fire behaviour indicates how a fire starts, flame develops and fire spreads. Although it highly depends on fuel characteristics and arrangement, it also varies according to associated fire weather. In this regard, by including fire behaviour as a component of fire potential, the strategic model addresses the importance of those synoptic conditions identified as the more hazardous for the study area. Big load, as a custom component of fire potential, could be easily interpreted as a fire hazard characteristic, as it reflects large accumulations of fuels. Even so, our intention when included as a stand-alone variable was to reflect the possibility of convective fire occurrence and behaviour, which cannot be fully addressed with existing fire simulation tools.

Another major advance, in terms of combining new tools and end user knowledge and demands to enhance acceptance, was the use of EMDS and its accompanying analytical components, NetWeaver (to evaluate the state of the landscape), and Criterium DecisionPlus® (to define management priorities areas and select management actions). Although EMDS has only been used infrequently in Europe up to the present time (Ray et al., 1998, Janssen et al., 2005, Puente, 2014, Pechanec et al., 2015), the system has demonstrated its value to solve diverse spatial problems aiming to allocate strategic restoration priorities during the past two decades, and recently also to define management actions per landscape unit (Reynolds et al., 2017). EMDS, as a decision support framework, copes with several of the requirements to needed to enhance acceptability of solutions for environmental problems, as in our case with the allocation of MASSs.

First, it allows combining innovative research results and expert knowledge based on ground experience. This aspect, not only tackles the issue of acceptance, but often helps to fill gaps in existing knowledge. For example, because there is not enough knowledge to define specific parameters to simulate large convective fires, driven by large accumulations of fuels (Lecina-Diaz et al., 2014), we agreed on a simple rule, defined by the topic big load (Fig. 2 and Table 2) for integrating the potential contribution of these fire scenarios in our fire potential evaluation scheme. Similar approaches were applied when defining other parameters shaping the levels of evidence within our logic model (Table 3), where a combination of literature on fire hazard and behavior (e.g., Hessburg et al., 2010), local rules on the relation between crown fire occurrence and forest structure (Pique et al., 2011), and expert readjustment was implemented.

Second, by using EMDS, and integrated logic and decision models, it is possible to provide a user friendly way to visualize all steps of the process, including relations, rules, criteria, weights and results (as for example the logic model in supplementary material). This aspect is crucial, as it not only avoids reluctance from end users to use results coming from a "black box", but enables a fluent two-way, interactive engagement between the researchers and end-users through process compression (Cash et al., 2003), which is required in any participatory planning process that aims at being implemented in the field.

The last aspect to consider, if the results of the study are to be implemented in the field, is flexibility. This feature relates to the intrinsic nature of the results provided, and the way in which they should be interpreted before being implemented. Through the methodology presented, we solved the issue of lack of harmonization regarding factors and criteria to be consider when allocating MASSs, as a preliminary step to allocate PEGs, and this also provides an interesting insight about the fuels management that needs to be undertaken. Still the results, from strategic and tactical planning assessments, were designed to allow an open discussion, and a final refinement coming from a final operations level decision process. As mentioned in the introduction, those areas that finally will support suppression maneuvers (PEGs) are areas associated with a pre-defined fire suppression strategy, for example opening a temporal and spatial window of opportunity for fire attack, thanks to the existence of infrastructures, a reduced fire intensity, and subsequently ameliorated working conditions. Those factors are considered when defining management priorities, but still there are other factors related to the expected fire behavior and fire spread patterns that have to be evaluated in the field prior to finally naming our high priority areas as PEGs, as they will impact suppression effectiveness. Selecting 1000 possible MASSs per fire scenario with a management recommendation for each unit, we exceeded the expected final size of the project. In that way, factors such as specific relief features within the MASSs, natural and administrative barriers, etc., can be used as operational constraints to reduce the number of final MASSs. Also, firefighters can visualize how fire could behave inside or nearby the MASS, and infer if the MASS accomplishes the requirements to be considered within the network of pre-suppression infrastructures as a PEG, and what will be the specific suppression strategy that can be associated to each PEG to add an additional priority layer. In this regard, it has to be stated that, based on our results, those priorities and actions defined under the most extreme scenario, *mistral*, are going to receive further consideration by firefighters, because they usually prepare for the worst conditions. Another aspect to be considered, when selecting the final number and allocation of MASSs, is the application of those fuel management actions recommended by our tactical analysis. Our actions refer to reducing fire hazard by aiming at those factors that create hazardous conditions, but these actions still have to be translated into more tangible fuel or forest management operations (Agee and Skinner, 2005). For example, at a stand level, pruning or prescribed burning will result in an increase of the canopy base height, while thinning will decrease the canopy cover and the area with high canopy bulk density, and an increase in the canopy base height when implemented as low thinning. The selection of the specific management operations should depend on a field assessment of the vegetation structure, combined with existing and accepted knowledge about the impact of forest management on the propagation of active crown fires, adapted to the forest conditions where they are to be applied (Pique et al., 2011). Because forests are dynamic by nature, and management operations are inherently point-in-time events within a management schedule (Beltrán et al., 2011), maintenance of fuel management on a MASS or any other place will be required over time to maintain treatment effectiveness. Consequently, being able to plan the implementation of management actions and maintenance of desired vegetation structure over time will further increase or decrease the chance of any of the predefined MASSs to be finally established on the field.

The methods illustrated and results obtained in this steady provide the means to make progress on solving a significant problem related to suppression preparedness in Catalonia, combining research based assessments and experts' involvement through the whole planning process. Similar approaches can be implemented for a variety of problems involving management for ecosystem restoration or similar problems that require spatial prioritization, where gaps of knowledge could be filled through expert knowledge, or where a transparent participatory process is required to enhance acceptability. Still, in the context of the present study, simply managing fuels on a reduced number of areas, in order to improve the efficiency and safety of forest fighters, is far from solving the overall problem of larger, more intense and more frequent fires occurrence and their associated impact. Once a fire reaches a certain size and intensity, suppression efforts have to rely on opportunistic windows of action (Fernandes et al., 2016a), although these may be enhanced by the allocation of PEGs. Even so, the highly unpredictable nature of extremely large fires, which have been continuously exceeding our predictions (Fernandes et al., 2016b), makes it difficult to ensure the complete effectiveness of PEGs regarding firefighters' security or any other expected impact, once extreme fires erupt. In this regard, only implementing more extensive fuel and forest management plans, with the capacity to modify fire behavior across large areas, and that are well integrated within a wider fire-smart approach (Hirsch et al., 2001; Fernandes, 2013) will have a major impact on the occurrence of large forest fires in Catalonia.

6. Endnotes

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

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Appendix A. Supplementary material

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