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Research article

Participatory multi-criteria evaluation of landscape values to inform wildfire management

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A B S T R A C T

Climate change is expected to increase the number of days with meteorological conditions conducive to uncontrollable wildfires. Thus, it is necessary to strengthen the capacity of wildfire-prone regions to minimize the adverse impacts of these wildfires by creating resilient landscapes. In this paper we develop a participatory multi-criteria evaluation to identify and map landscape values and prioritize areas according to these values in the Montseny Biophere Reserve (Catalonia, NE Spain). Then, we draft a wildfire management strategy to protect the areas that have been prioritized through selected fuel reduction sectors that would reduce wildfire intensity. Finally, we emphasize the added value of a participatory multi-criteria evaluation in the adaptation to and management of expected megafires. We find that the integration of landscape values through participatory multi-criteria evaluation has the potential to alter wildfire management strategies by adding fuel reduction sectors and changing their implementation order. However, the implementation of the planned fuel reduction treatments faces socioeconomic and institutional barriers that call for a deeper engagement with transdisciplinary project design and transformative science.

1. Introduction

Climate change is expected to substantially alter the Earth's wildfire activity (Moritz et al., 2012). Focusing down to Europe, its Mediterranean part has witnessed an increase in the length of fire weather seasons during the last decades (Jolly et al., 2015), and large wildfires have been catastrophic for entire regions due to socioeconomic losses and human casualties (San Miguel-Ayanz et al., 2013). A sharp increase in the number of days with meteorological conditions conducive to extreme wildfires is projected for the coming decades (Bowman et al., 2017), as well as in its summer burnt area (Turco et al., 2018; Moritz et al., 2012). More northern latitudes have recently experienced unprecedented wildfire events, turning the wildfire challenge into a continent-wide matter of concern (San Miguel-Ayanz et al., 2018). Indeed, fire services increasingly fear not being able to control devastating wildfires, especially those affecting wildland-urban interfaces (Castellnou et al., 2019).

Thus, there is an evident need to strengthen the capacity of wildfire-prone regions to adapt to extreme wildfire risk. Adaptive capacity is here broadly understood as the ability to implement social processes that minimize the adverse impacts of expected wildfires via the creation of resilient landscapes, which would be able to withstand this perturbation without major losses in ecological and social functions (Prior and Eriksen, 2013; González-Hidalgo et al., 2014; Abrams et al., 2015; Fischer and Jasny, 2017). One potential way to strengthen adaptive capacity is through participatory planning whereby public agencies, stakeholders,

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citizens and scientists design, implement and monitor fuel reduction treatments (Chapin et al., 2008; Butler and Goldstein, 2010; Everett and Fuller, 2011; Almstedt and Reed, 2013; Plana et al., 2015; Gazzard et al., 2016; Otero et al., 2018). Fuel reduction treatments have the potential to lower wildfire spread rates and intensity and thus minimize their adverse effects (Costa et al., 2011).

A crucial challenge of participatory wildfire planning lies in accounting for the vast diversity of landscape values and functions potentially affected by a wildfire (Rawluk et al., 2017). Diverse combinations of wildfire modelling and expert or participatory value assessment have been developed with the aim of including landscape values into adaptive management strategies (Morehouse et al., 2010; Alcasena et al., 2015; Otero et al., 2018). However, new efforts are needed to build more inclusive evaluation methods and to ensure that the results of participatory planning are effective for the adaptation of wildfire-prone regions, beyond purely academic exercises (Otero et al., 2018).

In this paper we deploy a participatory multi-criteria evaluation process (Munda, 2004, 2008; Proctor and Drechsler, 2006) and self-reflect on its potential to improve wildfire management. Our study shows that a participatory multi-criteria evaluation of landscape values may alter wildfire management strategies by adding fuel reduction sectors and/or changing their implementation order as compared to purely technical considerations of wildfire behaviour and management. We also identify relevant factors influencing the outcomes of a participatory multi-criteria evaluation of landscape values to inform wildfire management, and propose ways to deal with them in a transparent way.

In the following, we introduce the study region and the project (Section 2), we describe the methods employed (Section 3) and we present the main results (Section 4). Next, we reflect on our findings with particular attention on the added value of the participatory multi-criteria evaluation process to derive lessons learnt (Section 5). Section 6 concludes.

2. The study region

The Montseny Biosphere Reserve (MBR) is located in the Catalan Pre-coastal mountain range (Fig. 1). It is made up of eighteen municipalities in the counties of La Selva, Osona and Vallès Oriental, between the provinces of Barcelona and Girona. The total area is 50,167 ha and it has a population of about 52 thousand inhabitants. The altitudinal gradient and the presence of three biogeographical strata (Mediterranean, Euro-Siberian and Boreal-Alpine) give the MBR a great diversity of habitats and species in a relatively small territory. Far from being considered a purely ecological phenomenon, the diversity of the MBR is also the result of anthropogenic use of its resources throughout history (Boada, 2002; Roigé and Estrada, 2008). Activities such as agriculture, livestock breeding and logging, present since the Neolithic in varying intensities, have acted as an additional source of landscape diversity.

In the second half of the 20th century, socio-economic development decreased the importance of primary activities to the benefit of other sectors, such as industrial, tourist or residential activities (Sánchez, 2010). The depopulation of farmhouses, the migration of their inhabitants to towns and villages and the arrival of inhabitants whose economic activity is not related with the primary sector changed the landscape: forests expanded, crops and pastures were reduced, and the urban and industrial surface increased (Boada, 2002). At the same time, the appreciation of nature by a growing urban population led, in 1978, to a land planning scheme that protects Montseny as a Natural Park, as well as to the declaration of the MBR. Climate change comes to add to these transformations. In the second half of the 20th century, the average annual temperature increased by 1.2–1.4 °C, with considerable effects on ecosystems (Jump et al., 2007; Peñuelas et al., 2007; Peñuelas and Boada, 2003). All these transformations and changes contribute to increase the vulnerability of the MBR to wildfires (Otero and Arilla, 2015).

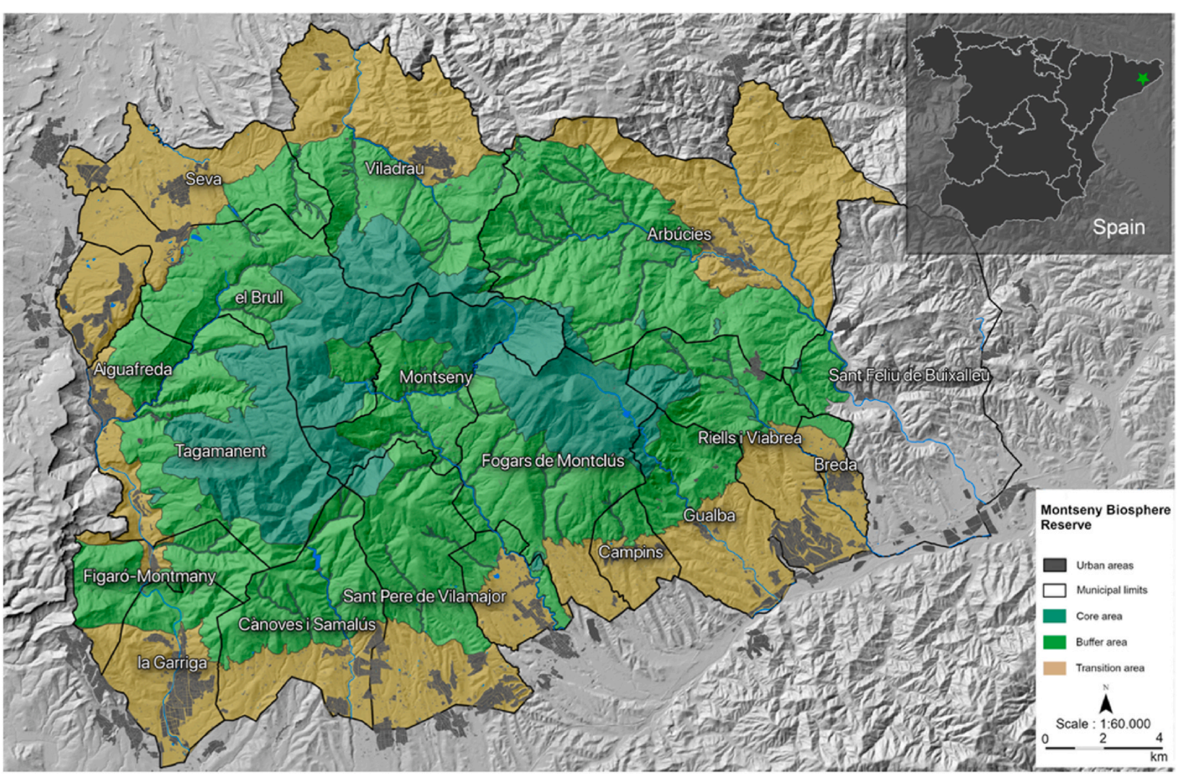

Fig. 1. Montseny Biosphere Reserve. Source: Own elaboration.

3. Methodology

Our methodology is characterized by the joint work between scientists and actors to find solutions to a particularly problematic situation (large wildfires), where uncertainty, conflicting interests and urgency shape public decision-making and call for an extended-peer community to face complex problems (Funtowicz and Ravetz, 1993).

To do so, we followed the methodological steps presented in Fig. 2, which combine scientific interdisciplinary work and public participation. Interdisciplinarity integrates theories and methods from different scientific disciplines to deal with technical incommensurability, i.e., multiple (disciplinary) descriptions of the same system. Public participation deals with social incommensurability, i.e., incorporating multiple and legitimate values that exist in society (Munda, 2004). (See Tables SM1 and SM2 that show the different sources of information used, from technical studies on wildfire risks to deliberations with regional and local actors).

To integrate expert and lay knowledge, a participatory process was designed at three different levels following Otero et al. (2018): regional, local and individual. The first two refer to the administrative capacity to implement policies, and/or to carry out socio-economic and environmental management. Regional actors are those that perform their functions at the whole MBR and beyond, and local actors operate within the MBR (e.g. at municipal scale). Therefore, social actors were expected to provide knowledge according to the territorial scale they operate.

Regional actors include those involved in wildfire prevention and territorial governance (e.g. technicians from the Territorial services of the Catalan Department of Agriculture, the Wildfire Prevention Technical Municipal Office of the Barcelona Provincial Council and of the Montseny Natural Park), actors who could provide information on landscape values (e.g. regional museums), as well as regional associations (e.g. Federations of Forest Defence Associations, Association of Forest Owners). Actors at local level included local institutions (e.g., municipalities) and local associations (e.g., Forest Defence Associations, Tourist Business Association). We organized several meetings with regional and local actors, either to validate the methodology, to identify landscape values and to present and discuss results. At the individual level, we invited citizens to participate in three exhibitions set up in municipal markets to get their opinion about places they value most (See Table SM2, which synthesizes the different meetings and activities carried out, their objectives and the participants).

3.1. Definition of the wildfire propagation scenario

This stage was aimed at defining the type of fire that can cause the largest damage to the MBR, the containment polygons and the corresponding fire propagation model. First, the type was defined based on the analysis of the following aspects: the causes of wildfires, the most important episodes, the types of fires, the danger (i.e. the possibility of a wildfire, assessed from past ignitions, orography and vegetation), the vulnerability (which indicates the damage that a fire can cause and is assessed on the basis of the presence of elements such as settlements, infrastructures or protected areas within forest lands or less than 500 m from them) (Generalitat de Catalunya, 2020) the synoptic conditions (Duane and Brotons, 2018) boosting wildfires and the homogeneous regime zones (i.e. areas of the territory with similar fire frequencies and homogeneous propagation patterns considering previous wildfires) (Generalitat de Catalunya, 2018; Castellnou et al., 2009; Costa et al., 2011; Piqué et al., 2011).

Next, we defined containment polygons according to the worst-case scenario defined previously. Containment polygons are the territorial units that firefighters use to assess the pattern of spread of fires, predict their extent and manage wildfires. Containment polygons are defined based on basins of different sizes, their limits are defined following either ridges or the valley bottoms, depending on the type of wildfire: bigger wildfires entail bigger containment polygons. Within a polygon, wildfire is expected to burn with a similar behaviour (Castellnou et al., 2019) and, when fire enters to a containment polygon, it is expected to burn down at once and completely. Third, we built a qualitative fire propagation model for the selected fire type and the containment polygons. It was defined according to the Campbell prediction system (Campbell, 1995) and indicates the intensity with which the fire would pass from one polygon to another. The intensity depends on the orientation of the slope (sunny or shady), the fire movement (uphill or downhill) and direction (upwind or downwind). Thus, a distinction can be made between maximum, medium, or low vectorial alignment of fire propagation forces (slope, wind and orientation), which generate situations characterized by being outside, at the limit, or within the extinguishing capacity, respectively. For example, a fire that spreads on a sunny slope, uphill and downwind is rated 3 out of 3 (maximum alignment). With adverse weather and fuel conditions, it would be out of extinguishing capacity of fire services.

3.2. Identification of landscape values

Landscapes are characterized by its biophysical features as well as by the socio-cultural perceptions of it (Termorshuizen and Opdam, 2009). Following this idea, we understand landscape values as an attachment or feelings that people develop with places, which are based on aspects of the landscape that are important to people (held values) or are the expression of the relative importance of the place in relation to other places (assigned values) ((Brown and Reed, 2000; Brown and Weber,

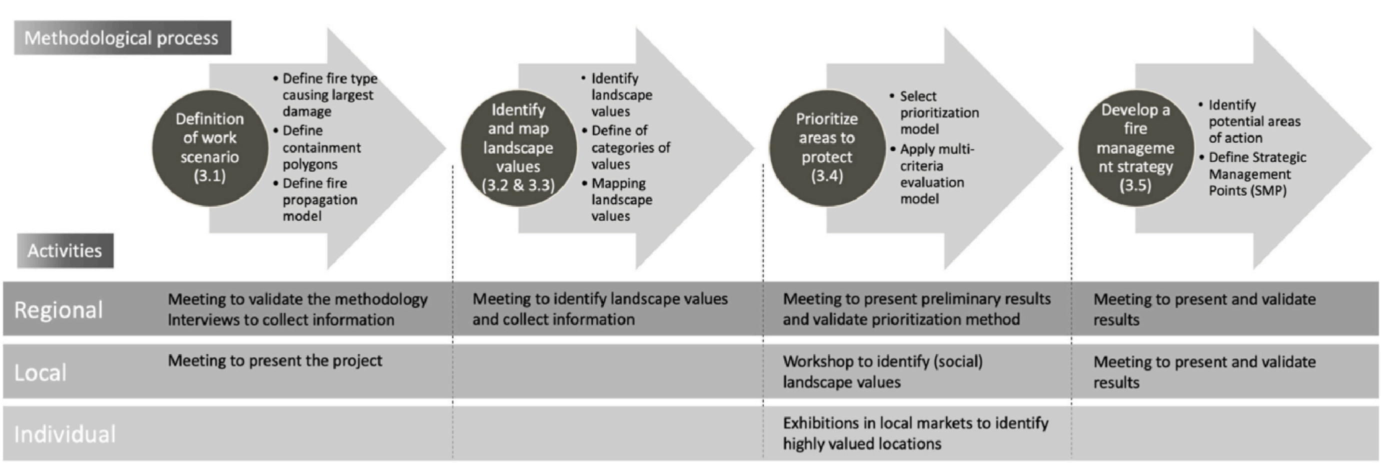

Fig. 2. Methodological process, levels of participation and aim of meetings and workshops. Note: The numbers in brackets indicate the sections of this article in which the different steps are explained.

2012; Penning-Rowsell, 1981)). According to (Brown and Weber, 2012), landscape values merge what is important for the individual (held value) to what is important for the individual in the physical landscape (assigned value). Landscape values can be instrumental or non-instrumental. The former refers to what provides tangible benefits to people such as economic value through socio-economic activities (e.g. agriculture, tourism, forest management), and the latter refers to something that is worth in itself. In fact, some landscape values can be considered as landscape features that have not necessarily a quantifiable worth, importance, esteem or utility, but that strongly attract and connect individuals to particular areas (Morehouse et al., 2010). The concept of landscape value can capture the holistic character of landscape-related benefits and values (Bieling et al., 2014) and would match people's way of framing and expressing landscape services, benefits and values (Bieling et al., 2014).

In this study, we identify components of the landscape that are valued by participants. Components can be classified in forms, relationships and practices, which are dynamic and coevolve in time. Forms refer to physical and measurable aspects of the landscape, including natural (e.g. landform, vegetation, water bodies) or anthropogenic (e.g. croplands, bridges, roads) elements. Relationships encompass people–people interactions, people–landscape interactions, and ecological relationships within the landscape. Practices include both human practices and ecosystem processes (Stephenson, 2008).

We combined data from both expert and lay knowledge. The data collected was iterated between groups of actors in the different meetings held along the project, and the database with the landscape values grew both qualitatively and quantitatively. Expert knowledge on landscape values was mainly obtained from the databases of the Public use plan of the Montseny natural park (Montseny Natural Park,), stored in the Montseny Information system. The Public use plan contains information on habitats and biodiversity, socio-economic activities within the park, built heritage and public use. The database of built heritage was validated and complemented by a technician of the Montseny Ethnologic Museum. Information on habitats and biodiversity was validated and complemented by technicians from the Biodiversity and Environment section of the Department of Territory and Sustainability, Catalan government, and technicians from the Natural Science Museum of Granollers (sources of information are presented in Table SM1). Then, the identified landscape values were classified in the following four categories: biodiversity, socioeconomic activities, built heritage and leisure, which were validated and used in subsequent meetings with the social actors.

Meetings and public exhibitions were carried out to identify landscape values from the local actors and individual citizens. Meetings with local actors included a presentation of the preliminary results of the project (e.g., wildfire regime, fire propagation model, landscape values already mapped based on expert knowledge). Then, the participants of the meetings were split in three thematic groups and were asked to discuss and locate in the map their most valued places. Inspired by Bieling et al. (2014) we asked three open questions: What are the areas, places or activities you value most? What area would you not want to lose in case of a big wildfire? What containment polygon would you protect first in case of wildfire? Answering these questions also facilitated the identification of landscape values not included in the databases. Local actors were also asked to prioritize the categories defined by the expert group and reflect on missing categories.

With this information, we introduced a new category called "Public values", which includes the places and (localized) practices valued by local actors and individual citizens. Since the participants of the meetings and exhibitions are not a representative sample of the population, we did not calculate the frequency of landscape values, and places and activities were counted only once, even though several places such as emblematic locations of the MBR were mentioned by many people.

3.3. Mapping landscape values

The information on landscape values collected from expert knowledge and public opinion (Section 3.2) was introduced into a Geographic Information System. Participatory GIS has been considered an adequate approach to map and analyse landscape values for land use management (Fagerholm and Käyhkö, 2009). Studies identifying landscape values usually analyse their geographical patterns – spatial distribution, frequency, intensity/density – the relative importance and the spatial relation between values (Reed and Brown, 2003; McIntyre et al., 2004; Brown, 2004; Fagerholm and Käyhkö, 2009; Garcia-Martin et al., 2017) and analyse the benefits provided by the landscape to human wellbeing (Fagerholm and Käyhkö, 2009; McIntyre et al., 2004; Brown, 2004; Garcia-Martin et al., 2017). In this case we apply a participatory GIS framework to identify and map landscape values, but we haven't considered the frequency and intensity with which the participants expressed the values.

When mapped, different elements were assigned different scores according to the importance within each of the 5 categories: biodiversity, socioeconomic activities, heritage, leisure, and public values. For instance, within the biodiversity category, elements of natural heritage with high and very high conservation interest were given a score of 4 and habitats of technical priority were given a score of 3. These values were assigned by the research group and validated with experts participating in the project. These scores are relative within each category, i.e. there is no relation between the scores assigned to elements of one category and the scores assigned to elements of another category. Five vector maps (one for each category) were generated. Then, a rasterization process of each vector map took place, in which the pixels of the raster maps have a score according to the elements contained in that pixel. For instance, a pixel in the biodiversity raster map containing a monumental tree (score 1 in Table 1) and located within a technical priority habitat (score 3 in Table 1) had an aggregated score of 4. Then, the score of each containment polygon under each category was calculated by aggregating the scores of all the pixels contained in it.

The mapping of values was carried out only in the "core" and "buffer" areas of the MBR, which represents 63.7% of the total (Fig. 1). Outside this area ("transition zone"), the availability of data was partial, and a systematic comparison between containment polygons was not possible.

3.4. Prioritization of the territory

The containment polygons identified in Step 3.1 were prioritized according to the number and diversity of values contained. First, containment polygons are ranked within each category according to the aggregated score calculated through the rasterization process. That is, within each category, containment polygons were ranked according to the amount of landscape values contained in them. Second, to obtain the final ranking of polygons, we applied a multi-criteria evaluation method. Multi-criteria evaluation is an analytical framework to support decision-making (Munda, 2008). It allows the analyst to compare a set of alternatives under a set of multidimensional criteria. In this case, the containment polygons are the alternatives to evaluate and compare, and the different categories of values are the evaluation criteria. Thus, a multi-criteria impact matrix is constructed with n rows and m columns, where n is the number of containment polygons to prioritize and m, the number of categories of values. Therefore, the multi-criteria impact matrix has been populated with the ranking of containment polygons for the biodiversity, socioeconomic activities, heritage, leisure and public values categories.

This information can be qualitatively analysed or a mathematical algorithm can be applied to aggregate criteria and obtain a ranking of polygons. There is a great diversity of multi-criteria methods, each one with its advantages and disadvantages. In this case, a simplification of the PROMETHEE method (Brans et al., 1986) was used (More

Table 1
Scores assigned to each element of the landscape identified by experts and general public.

Score[A]	Biodiversity	Heritage	Socio-economic activities	Leisure	Public values
5		– Buildings of heritage interest protected by law		– Highly frequented areas – Hiking trails	
4	– Elements with high and very high conservation interest				
3	– Technical priority habitats[B] – Potential habitat of *Calotriton arnoldi*[C]	– Churches and hermitages		– Private hunting areas, high captures	
2			– Urban cores and households	– Private hunting areas, medium captures	– Highly valued sites
1	– Monumental trees – Open spaces: Harvest meadows, Cropland, Cleared forest, Pastures	– Residential buildings – Agrarian infrastructure of heritage interest – Buildings and facilities of the of the MBR – Other elements with heritage interest (e.g. springs, graveyards, archaeological sites) – Historic resource extractions sites (e.g. mines, lime kilns)	– Camping sites, recreational areas and restaurants – Cropland and pastures – Managed forest plots – Resource extraction sites – Industrial areas.	– Private hunting areas, low captures	– Valued sites

Notes: A) The scores are relative within each category, i.e. there is no relation between the scores assigned to elements of one category and the scores assigned to elements of another category. The scores used in each category were defined together with experts participating in the project. B) Rivers, creeks and riparian areas are included in the Technical priority habitats. C) The potential habitats of the *Calotriton arnoldi* are explicitly included here because it is endemic of the Montseny park.

information on the method can be found in the Supplementary material). It is a non-compensatory method, which uses weights as importance coefficients and is easy to understand and communicate to non-experts; which are desirable characteristics when a multi-criteria model is used in decision-making processes (Janssen and Munda, 1999; Munda, 2004, 2008). Compensation refers to the possibility that very good evaluations under some criteria can offset very bad evaluations under other criteria. Non-compensatory methods do not allow this offsetting and, as a result, the best ranked polygons are those presenting a balanced diversity of landscape values across categories.

3.5. Development of a wildfire management strategy

The next step comprises a study of the areas that should be managed in order to help the fire extinction services to change the behaviour of a convective fire with west wind (i.e. the wildfire propagation scenario), considering the values and priorities identified in the previous stage. First, the fire propagation model was used to identify the fire multiplier polygons, that is, those containment polygons with a significant number of connections in maximum alignment of propagation factors to other polygons. Second, Management Promotion Areas (MPAs) were proposed to close fire entrances to and exits from multiplier polygons. A MPA is an area where active forest management to reduce fuel load is encouraged. This is done to reduce the alignment of the propagation factors from maximum to medium or low. Proper management of these areas would reduce the intensity of the fire and give options to extinguishing services to stop or manage the wildfire. Third, a fire management strategy was developed to address any possible fire access route in maximum alignment to the prioritized polygons, to reduce fire intensity to extinguishing capacity. The strategy also established an order for the implementation of the MPAs: temporal priority was given to actions that close the entrances of the fire to the prioritized polygons, which would reduce the impact on the most important landscape values. Finally, the strategy was discussed and validated with the regional actors.

4. Results

4.1. Wildfire propagation scenario and containment polygons

Based on the analysis of the region's wildfire regime, a west wind convection wildfire was defined as the worst-case scenario for MBR, which lead us to define the containment polygons and the propagation model showed in Fig. 3.

4.2. Landscape values of the MBR

The process of identifying and mapping values showed a remarkable amount and diversity of landscape values, highlighting both the social and ecological importance of the MBR. It also showed the values at stake when designing a strategy for wildfire management in a context of climate change. The maps presented in Fig. 4a–f are the result of this process for the different categories of landscape values.

Biodiversity (Fig. 4a) acquires the highest values in the central areas of the massif, such as the Pla de la Calma (where livestock activities have given rise to meadows and moors of very high ecological value), and around Turó de l'Home or Matagalls, the highest iconic peaks of MBR. In these areas we find the juxtaposed presence of different elements of high conservation interest, such as habitats of the Montseny brook newt (*Calotriton arnoldi*), meadows, mature forests, alders, unique flora, mosses, fungi, lichens and some birds and very high numbers of nesting points. In contrast, the peripheral area has lower values.

Built heritage (Fig. 4b) is spread across the MBR, which testifies the intense use that humans have made of Montseny, both historically and today. Built heritage is distributed in a more or less ubiquitous way, with some empty areas and others of high concentration, such as the Tordera valley or the Arbúcies stream.

Socio-economic activities (Fig. 4c) are present in much of the territory and acquire maximum values where we find inhabited areas or farmhouses with primary sector activities. It highlights a wide range of primary activities (farms with forestry activity, crops and pastures).

Regarding leisure (Fig. 4d), higher values are mainly concentrated in the southern periphery of the valued area. There, high-frequented places and especially productive hunting areas are juxtaposed, generating the maximum values.

Finally, the category of Public values, developed mainly from the contributions of local actors, highlights several areas that must be considered when planning fire prevention in the MBR (Fig. 4e). Among them we find Santa Fe, Turó de l'Home, the plain of La Calma, the hill of Tagamanent, the castle of Montsoriu and the stream of Arbúcies. The participants mentioned several reasons for the importance of these areas, such as these are places of identity, popular historical places, or places where social and traditional gatherings take place.

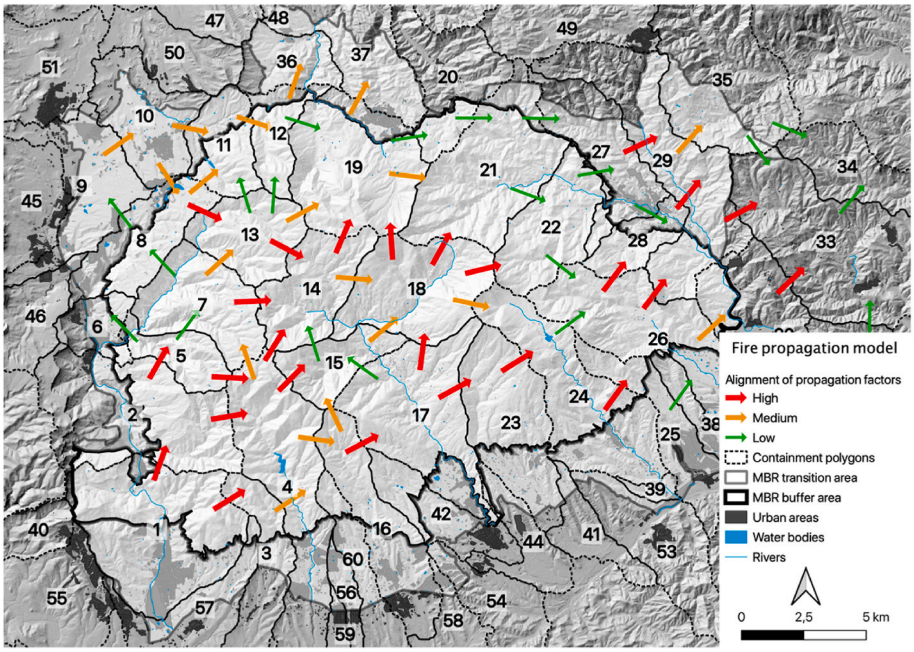

Fig. 3. Containment polygons and propagation model for a west wind convection wildfire. Note: The red arrows ⟶ represent high-intensity propagation (outside the extinction capacity); orange arrows ⟶, of medium intensity (at the limit of the extinction capacity), and green arrows ⟶, of low intensity (within the extinction capacity). Containment polygons are identified with numbers. Dark grey line delimit the "buffer" and "core" zones of the MBR (target of the valuation). Source: Own elaboration based on the expert knowledge of the GRAF (Generalitat de Catalunya, 2018). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

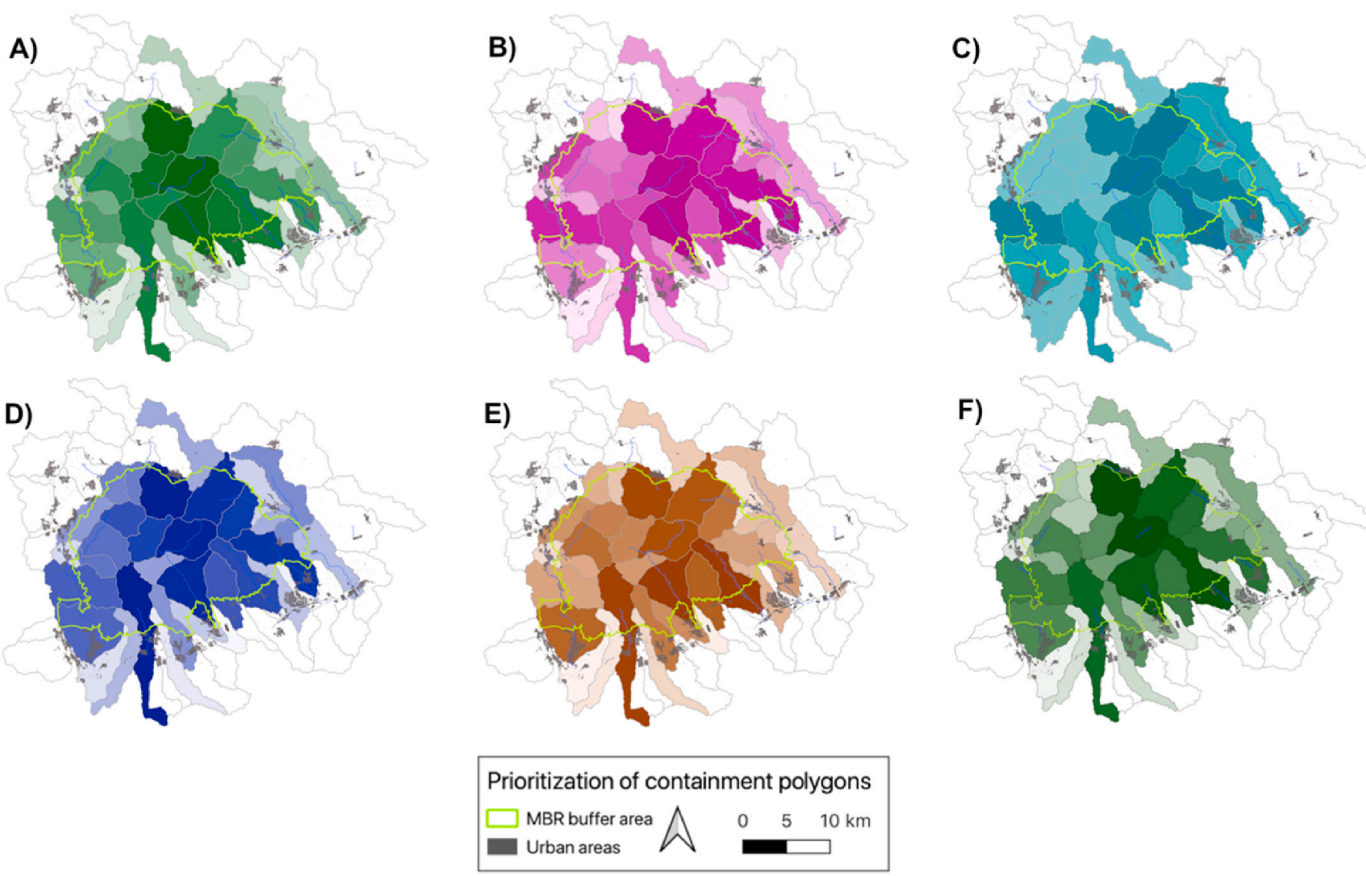

Fig. 4. Prioritization of containment polygons by categories. a) Biodiversity; b) Heritage; c) Socio-economic activities; d) Leisure; e) Public values; f) Climate change. Darker colors indicate higher priority. Source: own elaboration based on scores indicated in Table 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.3. Multi-criteria analysis of landscape values

Table 2 presents the multi-criteria impact matrix, which indicates the ranking of containment polygons under each category. To obtain the final ranking (extreme right column of Table 2), we applied the multi-criteria method explained in Section 3.4 and in the supplementary material. A first comparison assigning equal weights (i.e. 20%) to all categories was performed. Then, to check the robustness of the results, a sensitivity analysis was carried out by changing the weights of the categories: five additional comparisons were run in which we assigned, in each case, a weight of 30% to one category and 17,5% to the rest. When applying different weights, only minor changes occurred, and the 10 highly ranked containment polygons remained almost the same.

The results of polygon prioritization for different value categories show a general pattern: priority polygons tend to be in the centre and southwest of the massif (Fig. 4a–f).

4.4. Wildfire management strategy

The wildfire management strategy through Management Promotion Areas (MPAs) is a risk reduction approach to deal with large forest fires and is aimed at reducing the impact of fire on the landscape values set out in the previous sections. Fig. 5 shows the MPAs, which would be used to limit the extent of a convective fire with west winds, to facilitate the stabilization of fire tails and flanks, and to ensure access to extinguishing means. This is done by reducing the alignment of propagation factors from maximum to medium or low, so fire propagation is under the extinguishing capacity of fire services.

It should be noted that the MPAs are located mostly in the western and central part of the MBR, as they are designed to prevent a fire propagating eastward from growing.

Three types of MPAs can be seen in Fig. 5, which have been defined to manage a large convection wildfire driven by west winds starting in polygons 1 or 8 (located further west of the MBR). "MPAs technical

Table 2
Ranking of containment polygons under each category and final multi-criteria ranking.
Note: The first column indicates the different containment polygons, which are ranked according to the different categories of values in the subsequent columns. The last column indicates the ranking of polygons when applying the multi-criteria method and all categories are weighted equally. The cells highlighted in grey indicate the first ten polygons in the rankings under each category.

Nr. Polygon	Ranking under each category					Final Ranking
	Biodiversity	Socio-economic activities	Heritage	Leisure	Public values	
18	1	3	2	5	2	**1**
19	2	1	3	4	4	**2**
24	6	9	4	2	1	**3**
17	3	4	1	1	4	**4**
21	10	5	6	6	2	**5**
4	7	2	9	3	8	**6**
26	11	6	5	17	4	**7**
22	12	7	7	10	8	**8**
23	5	11	12	7	13	**9**
2	13	12	8	18	4	**10**
7	9	14	15	9	18	**11**
14	4	8	14	13	18	**12**
1	16	13	18	8	10	**13**
16	18	19	13	11	13	**14**
13	14	10	17	12	18	**15**
15	8	21	11	16	18	**16**
8	15	20	10	15	18	**17**
29	24	18	20	22	10	**18**
5	17	15	23	19	18	**19**
42	27	27	19	14	18	**20**
20	25	22	21	25	18	**21**
30	20	25	22	26	13	**22**
11	21	17	26	20	18	**23**
28	23	23	16	23	13	**24**
12	19	16	29	24	18	**25**
25	26	26	25	21	13	**26**
27	22	28	24	29	10	**27**
60	30	31	30	27	18	**28**
3	28	24	28	30	18	**29**
6	29	29	27	28	18	**30**
44	32	33	32	31	18	**31**
57	31	30	31	32	18	**32**
38	33	32	33	33	18	**33**

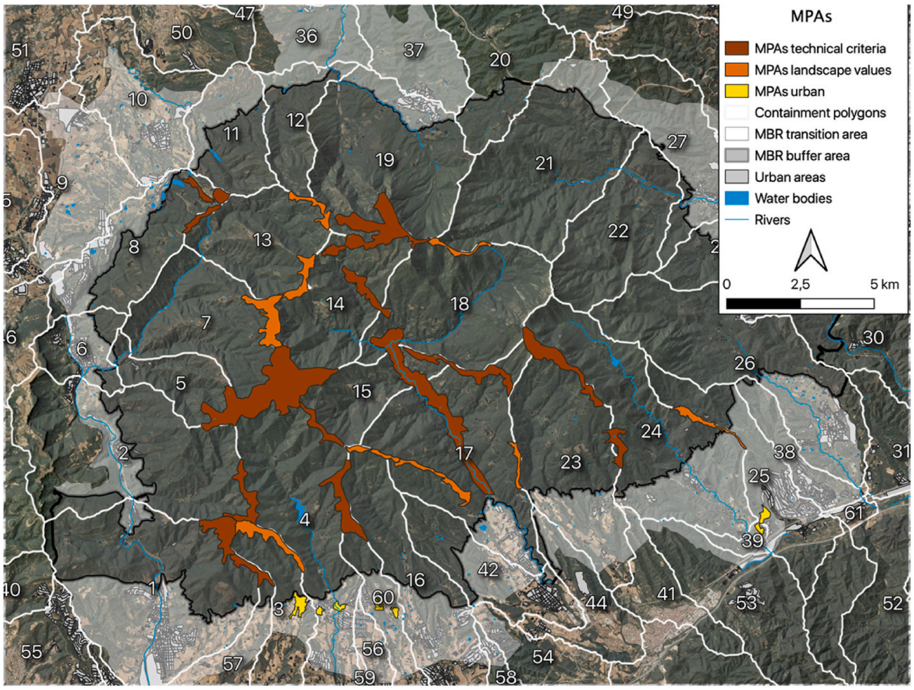

Fig. 5. Management promotion areas (MPAs) identified taking into account the behaviour of a convective fire with west wind and the prioritization of values in the Montseny Biosphere Reserve. The map differentiates between those MPAs identified only with technical criteria related to wildfire propagation (brown) and those MPAs that were added after analyzing the data on landscape values from the participatory process (orange). A third layer (yellow) shows an additional set of MPAs that could be added to protect the urban centers of the periphery (which were not included in the participatory evaluation, see methods). Source: Own elaboration based on the knowledge of the GRAF, (Generalitat de Catalunya, 2018). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

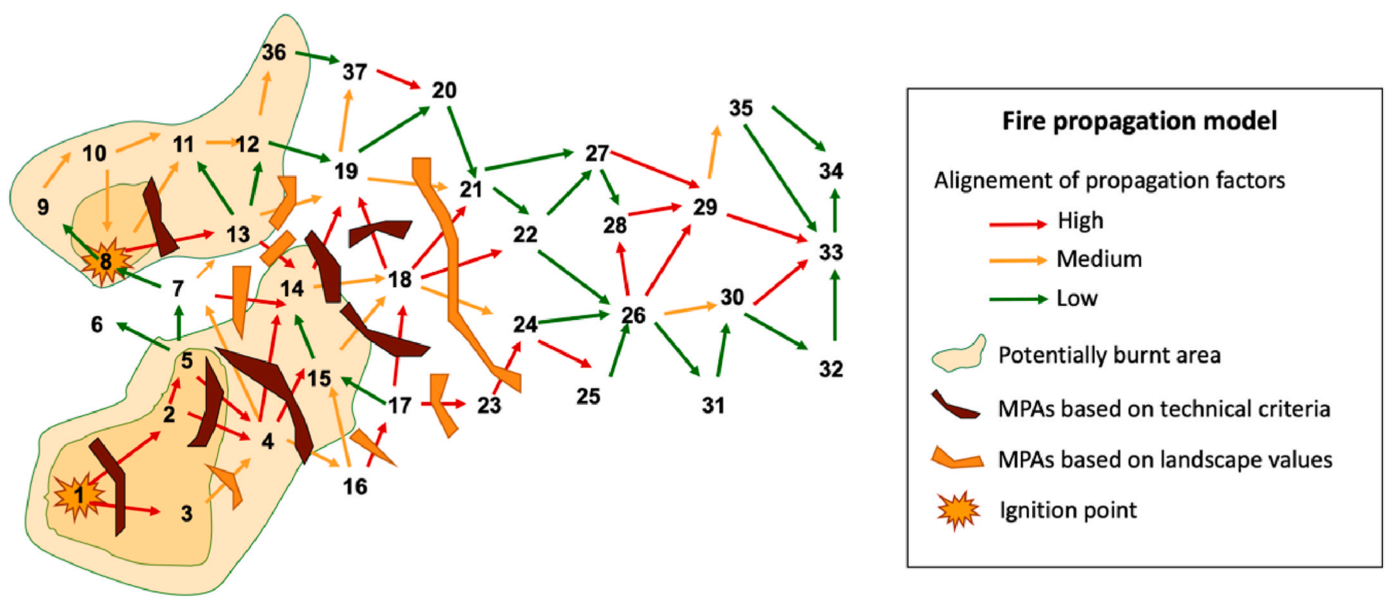

Fig. 6. Diagram of the propagation of two convective fires with west wind through the containment polygons (ignition points in polygons 1 and 8). Management promotion areas are schematically represented. It also indicates the possible perimeters of the fire depending on the success of the management strategy.

criteria" are those MPAs that were defined according to the criteria of the fire services, without considering the most valued polygons. The aim of these MPAs would be to avoid fire entering to and leaving from polygons 4, 14 and 18, which are multipliers polygons (See Figs. 3 and 6). "MPAs landscape values" are those MPAs that were defined to treat any possible path of fire in full alignment towards the most valued polygons (18, 19, 24, 17, 21 and 4) and/or reduce the intensity of fire down to extinguishing capacity. Finally, the "MPAs urban" are those MPAs defined to protect urban areas in the southern slope of the Montseny massif (these were not included in the participatory multi-criteria evaluation, see section 3 Methodology).

For a fire that starts in polygon 1, the first goal would be to avoid fire exceeds polygons 1, 2, 3 and 5. In case the fire reaches polygon 4, efforts would be focused on preventing the spread towards polygons 7, 14, 15 and 16. If this is not achieved, polygons 17 and 18 can be protected by cutting access from 16 to 17 and from 14 to 15 to 18 and 19. This would also protect polygon 24, another highly prioritized one. For a fire that starts in polygon 8, the initial goal would be to contain it within the polygon itself. If the fire goes to polygon 13 (a multiplier), efforts would be put to prevent it from passing to polygons 14 and 19. It was proposed to start working in the innermost MPAs of the massif (close to the priority central polygons) and end with the most peripheral MPAs.

The definition of the fuel reduction treatment, target vegetation structure, and operational usefulness of each MPA were left for a successive planning phase. Regarding treatments, forest management with machinery, prescribed burns, agriculture, extensive livestock, and a combination of these (e.g., clearing with machinery to leave the target structure and subsequent maintenance with prescribed burn or extensive grazing) were proposed. These actions were considered as an opportunity to reactivate the primary sector in the MBR. However, during the last project meeting, when this strategy was presented to social actors, several participants expressed their concern about the lack of funding to implement the MPAs. Several alternatives were proposed: to explicitly consider MPAs as an infrastructure against wildfires at the Catalan level (and budget them accordingly), to prioritize MPAs in calls for forest management subsidies, a scheme of payment for ecosystem services to forest owners that implement MPAs, or to include the MPAs in the Fire prevention plan of the MBR and its municipalities.

5. Discussion

We developed a method to include landscape values in the design of a wildfire management strategy aimed at adapting a fire-prone region to new climatic conditions, which can be associated with more intense fires.

The work presents two important novelties regarding the methodology developed by Otero et al. (2018). First, the creation of a map (Geographic Information System) in which each pixel is associated to a landscape value, as it was done by Morehouse et al. (2010). In theory, this allows wildfire managers to overlap the landscape values with different maps of fire containment polygons (designed to deal with different types of fires and climate change scenarios) and other layers with relevant information for spatial planning. Potentially interesting layers that could be added to refine our exercise are energy and water infrastructures (Alcasena et al., 2015).

Second, the incorporation of multi-criteria analysis, which allows the automated prioritization of polygons using a series of criteria that can be adjusted with successive phases of social participation. Multi-criteria evaluation has been used to allocate management areas based on fire potential and logistical factors important to fire fighters (Gonzalez-Olabarria et al., 2019). With our method, the allocation of such areas can be done by also considering landscape values from the affected communities.

5.1. Participation and valuation

Several approaches to identify landscape values have been developed, from purely expert approaches based on specific academic disciplines to more grounded approaches based on public participation. Purely expert-based analysis may fail to reflect the values expressed by those who feel belonging to the landscape, since the choice of the discipline and of the assessment method would determine what is perceived and considered as valuable (Stephenson, 2008). In fact, the pre-analytical decisions (i.e. those made before data collection and analysis) about the relevant attributes used to describe and represent a system, determine the methods of observation, the disciplines and, consequently, the results of the analysis (Kovacic and Giampietro, 2015). In our study, we have included an extra category of landscape values that come directly from the participatory process with local actors and citizens. In this sense, the use of the concept of landscape values was straight forward; there was little need to explain its meaning to participants, who could easily express what they value most from the landscape. In this way, we have expanded the pre-analytical categories defined according to expert knowledge or recorded in expert-based databases, by adding elements such as local or village festivities and/or fountain locations. Also, the inclusion of non-expert knowledge by means of participatory workshops was useful to perform a quality check and validate the methodology, the landscape values categories and the quality of the information used in the study.

At the same time, the inclusion of expert knowledge enabled us to identify landscape values beyond those areas that are well connected with roads and transport services (and thus are easily accessed by people), overcoming potential drawbacks of purely participatory processes. For instance, we now think that *highly frequented areas* (Table 1) should not be included as a landscape value. Most of these places are very well connected with roads and public transport, which determines which places are visited and which ones are not. In fact, most of highly visited areas coincide with the parking lots where information points are located (and visitors are registered). In any case, it is important to underline that our participatory process can be used to identify valued places, but not the degree to which a place is valued. The reason is that for the latter to be possible, we would need to reach a representative sample of the population and to assume that respondents have complete information about the benefits they obtain from landscape. Even in this case, the actors not willing or not able to participate, as well as future generations, would be underrepresented. In addition, the extremely broad range of values potentially affected by the expected wildfires makes it difficult to establish what is the “population” that should be sampled to estimate the value of landscape. As indicated by Otero et al. (2018) this should not constitute a problem as long as participatory processes are able to build legitimacy among actors and citizens in a long-term transformative engagement (See also Otero, 2022).

5.2. Multi-criteria evaluation

Regarding the multi-criteria evaluation, it should be noted that the optimal methods for this type of project are the so-called non-compensatory. Non-compensatory methods do not allow very good results under one criterion to compensate for very bad results under other criteria, as the criteria may represent the values, goals, and priorities of different social actors (Munda, 2004, 2008). The chosen multi-criteria method avoids trade-offs between categories of landscape values. However, the chosen method to calculate the value of each polygon under each category (Section 3.3) does allows intra-category compensation, since it works as a linear aggregation procedure. This means, for instance, that elements of biodiversity with high and very high conservation interest (that were given a score of 4 Table 1) equates to four monumental trees (which were given a score of 1), or that a legally protected church (with a score of 5) burning down in a wildfire is the same than five fountain (with a score of 1) being burn down.

Even though the scores given to different elements with different value were validated by experts in our workshops, the trade-offs mentioned above are difficult to assess even for an expert in the corresponding field. Moreover, it should be noticed that the scoring scheme (i.e. spread of scores, number of elements scored differently, and the value of the scores themselves) could influence the outcomes of the multi-criteria evaluation process. To test this, we performed a sensitivity analysis by changing the spread of scores, and no changes occurred in the prioritization of containment polygons.

However, for future experiences we recommend carrying out a two-stage multi-criteria evaluation process to rank containment polygons: an intra-category and an inter-category multi-criteria evaluation using the same non-compensatory multi-criteria method. Let’s consider, for instance, the intra-category comparison for the biodiversity category. In this case, 3 criteria would be used to rank the containment polygons: *i)* number of elements with high and very high conservation interest; *ii)* the technical priority and potential habitats of high interest, and *iii)* open spaces. In this way, it wouldn’t be necessary to assign a score to different landscape elements, and the ranking within each category would be obtained without allowing compensation between high and low-valued elements of that category. Then, the final ranking of containment polygons would be based on the rankings obtained for each category, as it has been done in this study.

We have learnt that there are several factors that would influence the outcomes of a participatory multi-criteria evaluation: the quality of the information populating the impact matrix (which is related to the landscape values included in the evaluation), the spread of the scores, the weight of the criteria, and the multi-criteria aggregation method. In general terms, the content of the valuation was contingent upon the actors included and their availability to provide input. As such, it was necessarily non-exhaustive and relevant values potentially influencing public priorities could have been left out, as it was also found in Otero et al. (2018). In this sense, we think that transparency (to make assumptions visible) and an inclusive participatory process are adequate ways of improving knowledge of the problem at hand and of controlling the quality of the information and assumptions used (Funtowicz and Ravetz, 1993; Gamboa, 2006; Munda, 2008; Garmendia and Stagl, 2010; Garmendia et al., 2010). We have carried out a multi-level and multi-actor participatory process, with several iterations allowing participants to raise their concerns on the methodology, the problem structuring and the analysis.

Where is the added value of participatory multi-criteria evaluation? To answer this question, it is worth recalling that the MPAs target strategic areas located in the borders of the containment polygons to prevent fire entering into them. Within a containment polygon, wildfire is expected to burn with a similar behaviour and assumed to consume it completely. Therefore, the output of the multi-criteria evaluation (i.e., ranking of most valued polygons) determines both which MPAs should be implemented and the order of implementing them (from the inside out of the MBR), to protect the most valued polygons. Our study shows that the participatory multi-criteria evaluation of landscape values has the potential to alter wildfire management strategies by adding fuel reduction sectors and changing their implementation order as compared to purely technical considerations of wildfire behaviour and management. Therefore, it can be considered as a spatially cost-effective adaptation strategy, which minimizes the loss of landscape values in the face of unavoidable catastrophic fires.

However, the MPAs that were planned during the project have not yet been implemented. One the one hand, this would have required more and better networking with local authorities so that they could integrate the MPAs in their wildfire prevention schemes (Otero et al., 2020). On the other hand, this is linked to the current residential and tourist function of the MBR, where primary activities have lost much of the economic viability they had in the past (Boada, 2002). In fact, most of the participants in the study considered it necessary to promote the primary sector and a "rural" life-style. In our meetings, it was argued that living in and from the landscape (e.g. farming, grazing and forestry activities) would both increase surveillance capacity and generate a landscape mosaic resilient to wildfires, as has been argued elsewhere (Mancini et al., 2018; Oliveira and Zêzere, 2020).

Moving from deliberative exercises to concrete action is one of the biggest challenges to reduce the risk of fires in a context of climate change. In fact, the viability of the creation of a resilient landscape through the promotion of primary activities (Aquilué et al., 2020; Otero, 2011; Regos et al., 2016); ; depends on larger changes in socioeconomic models and food systems (Otero and Nielsen, 2017).

Thus, to adapt European and other landscapes to climate change and wildfires of increasing intensity, the use of participatory multi-criteria evaluation should be complemented by a stronger effort in transdisciplinary research design (Lang et al., 2012; Moser, 2016) and transformative governance (Visseren-Hamakers et al., 2021), to coordinate policies across sectors (wildfire management, biodiversity conservation, agriculture, etc.) for the creation of functional and resilient landscapes.

6. Conclusions

This work developed a method to develop a wildfire management strategy based on landscape values, using a participatory multi-criteria evaluation methodology. It integrated expert and non-expert knowledge by means of participatory workshops and meetings, the review of technical documents and the inclusion of expert knowledge-based databases. Our method included the definition of the worst-case wildfire (wildfire propagation scenario), the identification and mapping of landscape values, the prioritization of wildfire containment polygons by applying a multi-criteria evaluation method and the development of a wildfire strategy based on MPAs. The implementation of MPAs is, in turn, a great opportunity to boost the primary sector and build a mosaic landscape resilient to large wildfires, but a greater engagement with transformative governance and transdisciplinary project design is necessary.

Credit author statement

Gonzalo Gamboa Conceptualization, Methodology, Software, Visualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration, **Iago Otero** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition, **Conchy Bueno** Visualization, Investigation, Data curation, **Etel Arilla** Investigation, **Helena Ballart** Investigation, **Laura Camprubí** Investigation, **Guillem Canalet**a Investigation, Writing – review & editing, **Gemma Tolosa** Investigarion, **Marc Castellnou** Conceptualization

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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