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Spatial multi-criteria analysis for prioritising forest management zones to prevent large forest fires in Catalonia (NE Spain)

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ABSTRACT

Large forest fires are one of the most common environmental issues in the Mediterranean region. In this study, we defined a set of indicators and criteria based on available spatial data to assess and prioritize management zones for preventing large forest fires in Catalonia (NE Spain). In total, 22 indicators were defined and grouped into 5 criteria. The process involved geospatial modelling using a Geographical Information System (GIS) and the Multi-Attribute Utility Theory (MAUT) analysis. The conducted MAUT analysis resulted in the development of rules for a more standardized assessment of priority management areas. This assessment is based on participatory evaluation and introduces a utility-function-based hierarchical spatial model. Within the model, each of the 5 criteria contains relevant information, including fuel hazard, potential fire behaviour, fire extinction accessibility, valuable resources at risk, and historical fire data, serving as the foundation for a comprehensive analysis of fire prevention measures. During the assessment, two distinct sets of weights were applied: one based on expert evaluation and another using equal weights. These weights describe the relative importance of the indicators within each criterion in the assessment of fire prevention measures. Our results reveal noticeable differences between the two applied approaches. In general terms, management priority levels showcase certain spatial aggregation patterns and spatial polarization characteristics. Our study underscores the importance of participatory planning for prioritizing forest management areas to reduce fire impacts and presents a methodological framework that facilitates such spatial assessments, utilizing tools that combine expert knowledge and scientific expertise. Therefore, the main focus of this study is not on the obtained results, but on the novel methodological framework used, which consists in combining geospatial modelling with MAUT and the participatory workshops for generating the utility rules. This framework allows participation of stakeholders which at the same time enlarges credibility and acceptance of the methodology and results.

1. Introduction

Fire has consistently been a prominent characteristic of the Mediterranean landscape. Spain exhibits the highest occurrence of fires and the greatest extent of burned area among countries in the region (Gonçalves and Sousa, 2016). Although large fires are relatively rare, they are recognized as significant disturbances that have profound negative consequences at the landscape, social, and economic levels (Bowman et al., 2011; Strauss et al., 1989). The occurrence of fires is influenced by different factors such as land abandonment, fuel accumulation, fire suppression, and climate change (Syphard et al., 2007). Due to considerable levels of uncertainty, methodological improvements and measures for fire prevention are required (Duane et al., 2015; San-Miguel-Ayanz et al., 2013).

The intricate nature of natural systems poses challenges for predicting fire occurrences due to the involvement and interrelation of diverse factors. In addition to weather conditions, topography, and vegetation characteristics, the Mediterranean region experiences a significant wildland urban interface, which further amplifies the likelihood of fire ignition through human activities (Rodrigues et al., 2022;

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Galiana-Martin et al., 2011; Ganteaume et al., 2013). In such a context, instead of solely focusing on response measures for large forest fires, a more effective approach to reducing their risk involves allocating Priority Management Zones. This approach is based on the Management Areas for Fire Suppression Support (MASS) framework that aimed at improving management actions considering the biogeophysical characteristics of the landscape, the potential for fire hazards, the capacity for fire extinction, fire exposure, and historical data (Ganteaume et al., 2013). Through a multifactor-based and solution complexity-oriented approach, the Priority Management Zones framework emphasizes the significance of the MASS methodological basis. It introduces participatory planning, selects consistent criteria and rules, and includes a robust spatial component, with the aim of efficiently allocating and managing resources for fire prevention.

Spatial planning, encompassing both strategic and tactical components, plays a crucial role in the effective assessment of forest fire management (Gonzalez-Mathiesen et al., 2021; Gonzalez-Olabarria et al., 2019). Firstly, strategic planning establishes objectives and prioritizes areas where silvicultural treatments should be applied. Subsequently, tactical planning facilitates the optimal selection of management actions for the designated areas, thereby minimizing risks to suppression resources and firefighting personnel. This process optimizes resource allocation and enhances cost-effectiveness (Gonzalez-Olabarria et al., 2019). When combined with fuel management actions, guided by the principle that modifying fuels across a landscape can influence fire behaviour, this integrated approach creates greater possibilities for successfully confining fires during suppression measures (Dimopoulou and Giannikos, 2004; Kirsch and Rideout, 2005). This approach emerges as a necessity in response to frequent constraints in the applicability of fire management assessment, primarily stemming from inadequate economic resources dedicated to this purpose. Additionally, when implemented in the allocation of priority zones for management, it considerably simplifies the process of selecting the optimal management actions if a subsequential tactical planning process is implemented. This research focuses on the strategic aspect of the landscape planning process.

Landscape indicators refer to a measurable variable that characterize the condition of the environment and provide relevant information that helps in fuel planning (Kosmas et al., 2014). The analytical framework used to assess Priority Management Zones involves initially identifying influential factors that can be represented by indicators, followed by data standardisation, determination of criteria importance and consideration of relationship between them (De Brito et al., 2018; Adab et al., 2013; Jahdi et al., 2016). The careful selection of suitable criteria and indicators plays a critical role in environmental evaluation, as this choice has a substantial impact on the assessment outcomes (Kurka and Blackwood, 2013). Despite ongoing discussions, there remains a lack of consensus regarding the most effective selection of criteria and corresponding indicators (Hong et al., 2019). This selection depends on the topic specificity and data availability and varies depending on the study area and its geographical characteristics. The utilization of participatory analysis in the process of defining criteria contributes to enhancing the validity of selected indicators and promotes the acceptance and durability of environmental decisions (Gamboa et al., 2023). This approach incorporates expert knowledge, thereby reinforcing the robustness of the decision-making process (Carrick et al., 2022). Within the context of identifying areas for prioritizing management actions aimed at mitigating the risk of large forest fires, participatory analysis emerges as the most objective and comprehensive tool for defining pertinent criteria and parameterizing the associated indicators. This approach is particularly valuable given the substantial complexity of the environmental system and the inherent heterogeneity of the criteria that need to be taken into account (Smith et al., 2007; Moore et al., 2002; Aguilar and Montiel, 2011).

Due to the intrinsic spatial nature of forest fires, the incorporation of spatial dimensions into multi-criteria analysis of forest fire prevention measures and prioritised management areas is deemed essential. Furthermore, the utilization of georeferenced data in such analyses significantly enhances decision-making processes, facilitates the representation of results, and enables the implementation of geographically targeted management actions within specific spatial units (Sakellariou et al., 2020; Guarniéri and Wybo, 1995; Akay and Erdoan, 2017). With the increasing availability of geospatial data, particularly remotely sensed data, and the incorporation of expert participatory planning to identify relevant criteria, more improved decision-making processes and outcomes have been achieved (Thompson et al., 2020; Jaiswal et al., 2002; Nuthammachot and Stratoulias, 2021). The synergistic use of geographical information systems (GIS) and participatory-based multi-criteria models has demonstrated several strengths in applications related to forest fuel planning (Gigović et al., 2018). This framework enables decision-makers to transparently choose and standardize indicators and criteria by integrating stakeholder preferences into a quantitative spatial-based model (Erden and Coşkun, 2010; Roe, 2012), having high applicability in the strategic prioritisation of areas for effective allocation of Priority Management Zones.

In this study, we focus on the selection and parameterization of indicators and criteria for prioritizing management zones with the goal of preventing large forest fires in the Catalonia region of Spain. Multi-Attribute Utility Theory (MAUT) was employed in conjunction with spatial modelling in Geographical Information Systems (GIS) (Roe, 2012). Expert-knowledge-based participatory planning defined a set of pertinent indicators and criteria for Priority Management Zones allocation, along with relevant rules for constructing a hierarchical spatial model. Additionally, two distinct sets of weights were established and utilized to evaluate the relative significance of the chosen criteria, enabling the identification of prioritized areas. The resulting management priority maps aim to provide the best cost-efficient solutions and allocate spatially the areas that exhibit high susceptibility to fires, thereby emphasizing the need for proactive management to prevent large forest fires and subsequently reduce fire risk by enhancing prevention activities.

2. Methodology

2.1. Study area

Our research was conducted in Catalonia region (north-east Spain), where about 42% of the approximately 32,000 km^2 of land is categorized as wooded forest areas (Fig. 1) (Land Cover Map of Catalonia v4 2009). Of the total forested area, approximately 75% is under private ownership, where significant fragmentation hinders the execution of effective forest management (Coll et al., 2011). The region exhibits significant orographic variation, encompassing altitudes spanning from sea level to over 3000 m (Roces-Díaz et al., 2018). These elevational differences exert considerable impacts on the local climate, which ranges from semi-arid conditions to subarctic climates with Mediterranean influences, affecting fire behaviour characteristics. Over the past three decades, over 21,686 forest fires have been recorded in Catalonia, resulting in the burning of approximately 265,000 hectares of land (Krsnik et al., 2020). To define spatial fire management units and compute needed metrics we utilized stand-level information extracted from the Spanish Forest Map 1:25,000. In entirety, a total of 238,096 polygons were employed to conduct the MAUT analysis.

2.2. Conceptual design

The primary aim of the research is to define Priority Management Zones to prevent large forest fires by establishing their spatial boundaries through cartographic representation. To achieve this objective, the project was executed in three sequential phases (Fig. 2):

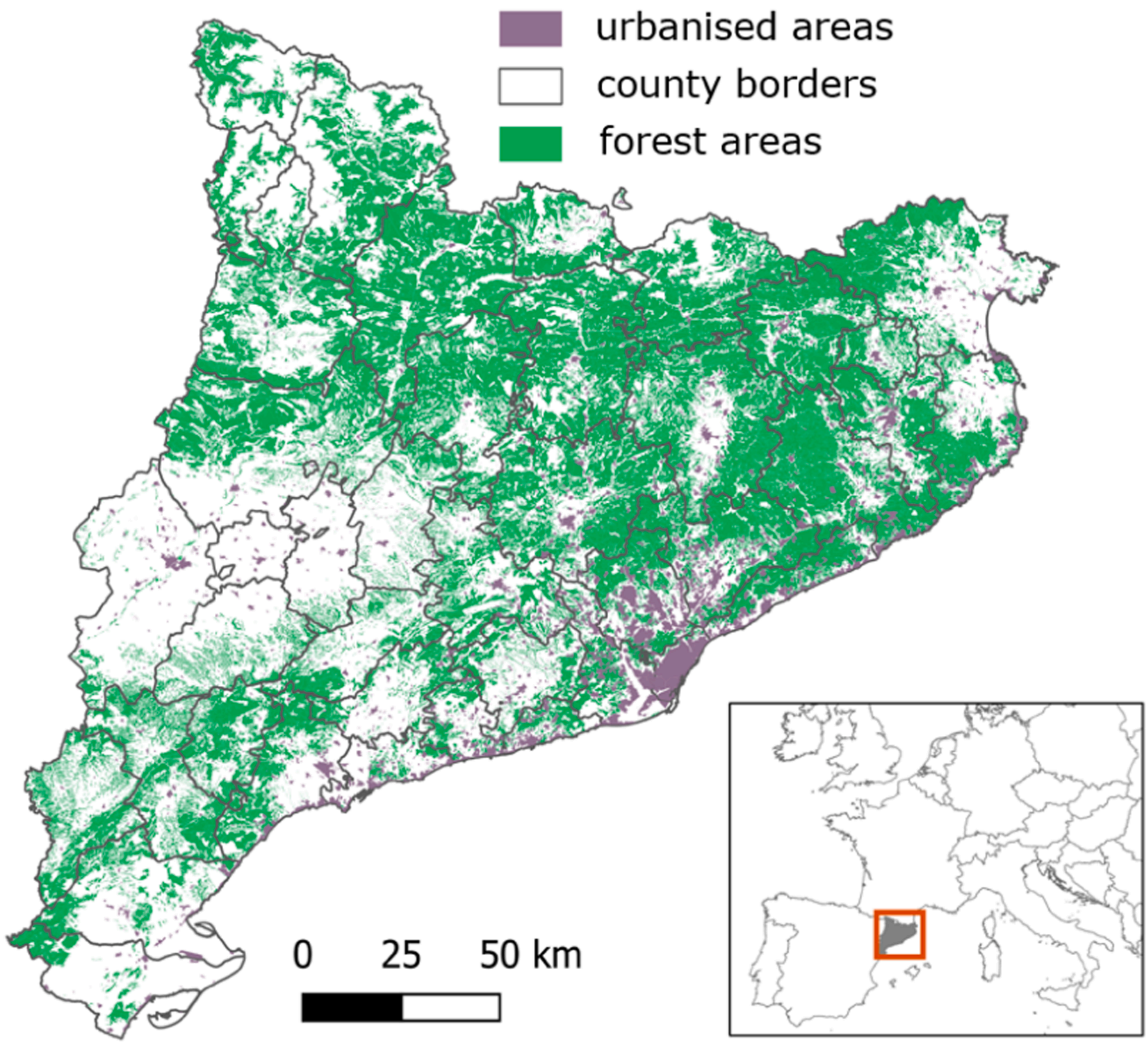

Fig. 1. Location of the study area.

1. In this step, an initial analysis of data availability was done to determine the spatial indicators and criteria that influence forest fire behaviour/potential and prioritisation of forest fire prevention measures.
2. The second phase involves the MAUT analysis, where data normalization using utility functions was performed, and weights through participatory planning were assigned, to the identified indicators and criteria.
3. In this final step, maps were generated that quantify the prioritization of management measures aimed at forest fire prevention. This quantification is achieved through the amalgamation of normalized data, represented as utility scores, and the criteria with assigned weights.

2.2.1. Definition of indicators and criteria for fire prevention measures

The initial stage in conducting a thorough analysis of forest fire risk involves establishing indicators and criteria that influence fire prevention measures. A crucial criterion was to define as many indicators as feasible to effectively capture existing biogeophysical processes, fire behaviour, fire extinction capacity, fire exposure risk and historical fires data, and facilitate the assessment of Priority Management Zones allocation. Thus, an exhaustive evaluation of available data was undertaken to identify spatial information suitable for defining and subsequently quantifying priority management zones. Additionally, an expert participatory process based on focus-group-principles was conducted to assist data selection, verification and definition of adequate variables. In total, 22 indicators were selected and defined, grouped in 5 categories, that for purpose of this study are denominated as criteria (Table 1). We utilized primary data and performed geoprocessing tasks using ArcGIS software to achieve the appropriate units and thresholds for each indicator, based on expert knowledge. Simulations using FlamMap (Finney, 2006) were employed to obtained fire behaviour indicators.

2.2.2. MAUT analysis

After defining the indicators for Priority Management Zones allocation, in this step we proceed to conduct the MAUT analysis. The MAUT analysis involves eliciting utility functions and weights, and calculating overall utility scores from the aggregated model (Fig. 3). The applied model takes the form of a hierarchical structure, in which Priority Management Zones allocation, situated at the top of the model tree, is delineated by five criteria (C1–C5). Each criterion is delineated by a collection of indicators (I1–I22), which varies from 3 to 6, contingent on the availability of spatial data.

Indicators represent the lowest level of the model, with data being their sole antecedents. Through the application of fuzzy membership functions, each observed dataset is transformed into utility values, spanning from 0 to 1. Utility values serve to quantify the level of support for the logical statement associated with each indicator, normalize and standardize the values, and enable direct comparison between variables

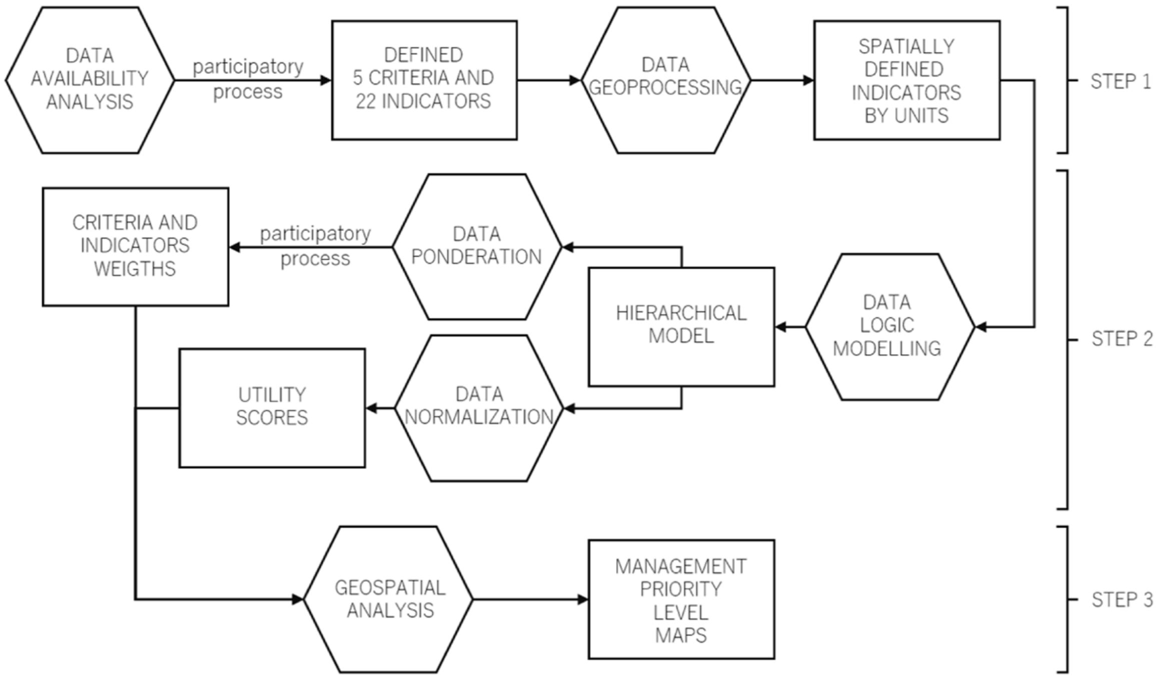

Fig. 2. Schematic design of the study workflow.

at all levels of hierarchical tree model. For instance, referring to the example illustrated in Fig. 3 (I17), forested areas situated in proximity to roads suitable for fire engine access, would be assigned higher utility values by the model, indicative of a reduced risk of big forest fires. Conversely, the model assigns lower values to stands located farther away from suitable roads.

The designation of thresholds that discern low or high utility is performed separately through participatory evaluation for each indicator, employing a total of 22 distinct fuzzy membership functions (Table 2). Once utility scores are assigned to each indicator, these values are propagated upward through the model hierarchy, ultimately resulting in the assignment of utility values to all levels within the hierarchy.

The significance of each indicator in defining criteria is indicated by fix weights, each allocated through collective evaluation by experts through the analytic hierarchy process (AHP) based analysis. In this analysis, each indicator was compared to all other indicators within the same criteria group, to obtain preliminary weights. Each criterion was also assigned a weight (W1-W5). In this case, two distinct sets of weights were utilized: one assigned based on expert knowledge through participatory evaluation (Approach 1), and another employing equal weights for all criteria (Approach 2). The weights designate the relative importance of each criterion for the allocation of Priority Management Zones. The weights utilized in this study are preliminary and subject to change. They are subjective and dependent on the territory; hence, they are presented in the Results section.

2.2.3. Cartographic representation of fire management priority zones

The cartographic representation of fire Priority Management Zones aligns with the spatial visualization of utility values attributed to the uppermost hierarchical unit of the model. This led to the creation of two distinct maps, each following a distinct approach in terms of assigning weights to defined criteria. Across both maps, a utility value was assigned to each of the 238,096 polygons, reflecting the level of management priority based on criteria utility levels and applied weights. For cartographic representation, 7 priority categories (from very low to very high) were created using equal-intervals-based separation method (14th percentile). The delineation of these categories is subjective and established exclusively for visualization purposes, with potential adjustments contingent upon specific research objectives.

3. Results

This paper outlines the methodological foundation for the improved allocation of Priority Management Zones aimed at mitigating large forest fires. The framework involves a participatory-based assessment and selection of pertinent indicators for Priority Management Zones. These indicators are organized into criteria, offering spatial information crucial for defining and delineating Priority Management Zones. Weighting for each indicator and criterion is determined through participatory expert-based evaluation. The definition of rules and modelling is carried out using a utility-function-based participatory planning approach, enabling a more standardized methodological framework for conducting complex, solution-oriented, multi-criteria spatial analyses (Fig. 4). The paper presents and discusses preliminary results obtained to test and validate the proposed methodological approach.

The geospatial distribution of utility scores for each of the 5 criteria employed in the study reveals distinct patterns across the study area. Fire behaviour demonstrates high utility levels across a significant portion of the territory, with predominantly agricultural and urbanized areas experiencing lower utility scores. Fuel hazard and exposure criteria exhibit similar spatial aggregation, with high utility scores observed in the northern and coastal regions of the study area. However, there are notable differences in absolute values between these criteria. While fuel hazard shows significant disparities between high and low utility values, the differences are more subdued in the case of exposure criteria. Conversely, the spatial distribution of accessibility values is influenced by topography, resulting in lower utility values in the northern (Pyrenees) and pre-coastal (Catalan Coastal Range) sections of the study area. Lastly, utility values pertaining to continuity criteria are predominantly low, except in the extreme northeast sector of the territory.

The results regarding Priority Management Zones allocation demonstrate disparities in the spatial dispersion of management priority levels between the two employed methodologies, nevertheless, the

Table 1
Selected indicators (I) and criteria (C) to evaluate and allocate Priority Management Zones.

Criteria and indicators	Description	Applied threshold and/or unit	Sources
Fuel hazard (C1)			
Canopy base height (I1)	% of the stand area with values below the established threshold	5.5 m	(Krsnik et al., 2020; CTFC 2023)
Canopy cover (I2)	% of the stand area with values above the established threshold	50 %	(Krsnik et al., 2020; CTFC 2023)
Canopy bulk density (I3)	% of the stand area with values above the established threshold	0.15 km/m^3	(Krsnik et al., 2020; CTFC 2023)
Understory cover (I4)	% of the stand area with values above the established threshold	30 %	(Coll et al., 2011)
Vertical continuity (I5)	% of the stand area with values below the established threshold	5 m	(Krsnik et al., 2020; CTFC 2023)
Fire behaviour (C2)			
Fire intensity (I6)	% of the stand area with values above the established threshold	350 Kw/m	(Krsnik et al., 2020; Finney, 2006; CTFC 2023)
Spread speed (I7)	% of the stand area with values above the established threshold	1.2 km/h; 0.33 m/s	(Krsnik et al., 2020; Finney, 2006; CTFC 2023)
Flame height (I8)	% of the stand area with values above the established threshold	3 m	(Krsnik et al., 2020; Finney, 2006; CTFC 2023)
Exposure (C3)			
Urbanised areas (I9)	Distance to the closest urbanised area from each stand centroid	m	(Generalitat de Catalunya, 2023)
Recreational areas (I10)	Distance to the closest homologated hiking trail from each stand centroid	m	(Homologated hiking trails network, 2021)
Capitalisation (I11)	Comparison between mean basal area and the established threshold	40 m^2/ha	(Generalitat de Catalunya, 2023)
Protected nature (I12)	Distance to the closest key areas of Natura 2000 network from each stand centroid (adapted by the Government of Catalonia)	m	(Generalitat de Catalunya, 2023)
Cultural heritage (I13)	Distance to the closest architectonic, archaeological or paleontological monument from each stand centroid	m	(Generalitat de Catalunya, 2023)
Strategic infrastructure (I14)	Distance to the closest powerline or highway from each stand centroid	m	(Generalitat de Catalunya, 2023)
Accessibility (C4)			
Aspect (I15)	Terrain aspect	%	(Krsnik et al., 2020; CTFC 2023)
Road density (I16)	Density of path and roads wider than 2.5 m (suitable for fire engines) within each stand	km/km^2	(Generalitat de Catalunya 2023)
Road distance (I17)	Distance to the closest path or road wider than 2.5 m (suitable for fire engines) from each stand centroid	m	(Generalitat de Catalunya 2023)
Water availability (I18)	Distance to the closest water body or well with the capacity of more than 50 m^3 from each stand centroid	m	(Generalitat de Catalunya 2023)
Strategical management areas (I19)	Distance to the closest area classified as strategical management area from each stand centroid	m	(Generalitat de Catalunya 2023)
Continuity (C5)			
Fire risk level (I20)	Fire risk level based on intrinsic forest fire characteristics	Categorical 1–4	(Piqué et al., 2011)
Agroforested areas (I21)	% of agroforested area within 1 km buffer from each stand centroid	%	(Krsnik et al., 2020; CTFC 2023)
Return period (I22)	Return period in case of forest fire	years	(Piqué et al., 2011)

spatial pattern exhibits resemblances in its characteristics. Broadly speaking, Approach 1, compared to Approach 2, records elevated priority values across a significant portion of the forest-covered study area, notably amplifying the extent of categories classified as medium-high priority and high priority. Simultaneously, there is a reduction in the scope of areas designated as medium priority. Areas lacking forest cover, predominantly categorized under lower priority categories, exhibit comparatively diminished priority levels within expert-evaluation-weights-method as compared to equal-weights-method. Consequently, in a general context, Approach 1 showcases a more pronounced polarisation in values between forested and non-forested regions, heightening management priority levels within forested zones while diminishing them within non-forested zones. Approach 2 discerns these trends, yet it presents more evenly distributed values across the study area (Fig. 5).

According to Approach 1, the zones classified as very high priority exhibit limited spatial coverage and are situated in the northeastern and central coastal sectors of the study region. Areas of very high priority are spatially constrained and isolated from each other, forming clusters in small units in the north and exhibiting complete disaggregation in the south. Zones categorized as high priority align with the central continental section of Catalonia, extending to both coastal and pre-coastal ranges, as well as the maritime Pyrenees. They encompass a substantial portion of the study area and are aggregated into several spatial clusters. High-priority areas consistently display high utility values for at least 4 of the criteria utilized, with exposure being the most frequently observed criterion registering somewhat lower utility scores. Within the study area's northern half, a prevalence of medium-high priority is observed, particularly evident in the Pre-Pyrenees and Pyrenees regions, where it coincides with zones assigned a medium priority level. Medium-high and high areas are primarily characterized by elevated fuel hazard, fire behaviour, and exposure levels, along with lower accessibility and continuity utility scores. Encompassing a significant spatial extent within the study area, they exhibit a predominantly aggregated spatial pattern. Zones characterized by medium-low, low, and very low priority levels largely overlap with extensively urbanized and/or industrialized zones, as well as regions dominated by agricultural activities. These areas are defined by low utility values of Al least 4 criteria, but commonly registering high accessibility values (Fig. 5a).

Approach 2 demonstrates nearly comparable outcomes to Approach 1 within the northeastern segment of the study area. However, in the central continental and coastal zones, numerous regions previously designated as high priority areas under Approach 1 now receive medium high priority rankings. Similarly, in the Pre-Pyrenees and Pyrenees sector, considerable expanses of land are categorized as medium

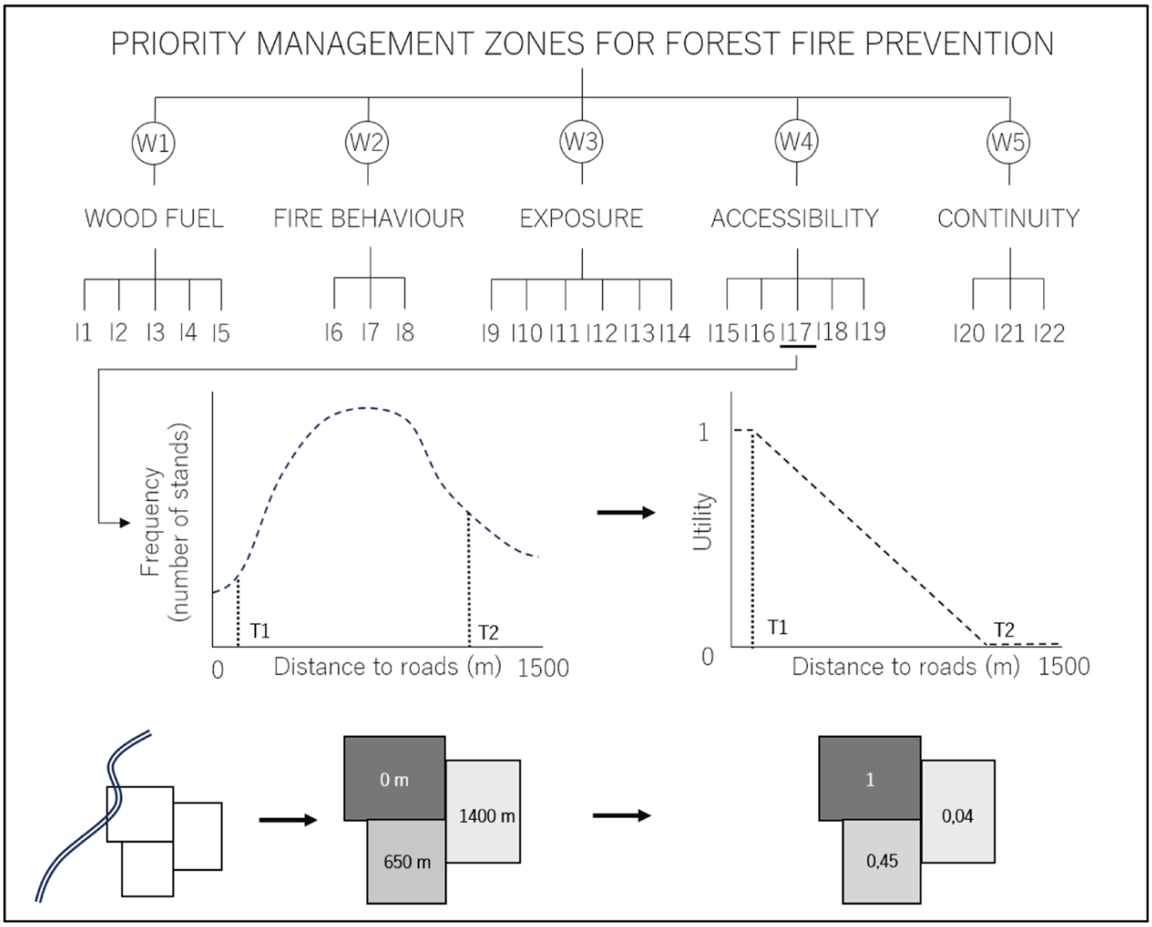

Fig. 3. Schematic design of the applied model and utility value assignation.

Table 2
Established threshold values for assigning utility functions.

Indicators	Unit	Utility 0 threshold	Utility 1 threshold
Canopy base height (I1)	%	30	60
Canopy cover (I2)	%	30	60
Canopy bulk density (I3)	%	30	70
Understory cover (I4)	%	30	70
Vertical continuity (I5)	%	0	25
Fire intensity (I6)	%	10	50
Spread speed (I7)	%	10	50
Flame height (I8)	%	10	50
Urbanised areas (I9)	metres	7500	0
Recreational areas (I10)	metres	1000	0
Capitalisation (I11)	m^2/ha	0	40
Protected nature (I12)	metres	1500	250
Cultural heritage (I13)	metres	5000	250
Strategic infrastructure (I14)	metres	2500	0
Aspect (I15)	%	45	5
Road density (I16)	km/km^2	180	90
Road distance (I17)	metres	1000	150
Water availability (I18)	metres	1200	0
Strategical management areas (I19)	metres	175,000	1300
Fire risk level (I20)	Cat. 1–4	1 = 0; 2 = 0.33; 3 = 0.66; 4 = 1	
Agroforested areas (I21)	%	80	20
Return period (I22)	years	500=0; 100=0.5; 30=1	

priority, contrasting with their medium high priority designation in Approach 1. Concurrently, significant portions of areas marked as very low priority and low priority in Approach 1 are reclassified as medium low priority and low priority, respectively, following the principles of Approach 2 (Fig. 5b).

4. Discussion

In this research, we undertook the task of selecting and parameterizing indicators and criteria to prioritize management zones, aiming to mitigate the occurrence and impact of large forest fires in the Catalonia region of Spain. Given the absence of consensus on the most effective indicators for modelling and mapping the priority forest management areas to prevent large forest fires, our objective was to create a spatial model that encompasses all pertinent stressors, providing comprehensive information about the biogeophysical characteristics of the area. The availability of spatial data presents challenges in identifying all pertinent indicators, leading to an incomplete representation of the geospatial reality (Chuvieco, 2009). Concurrently, the outcomes and their interpretation are heavily reliant on the chosen indicators and their accuracy (Short, 2014). To address this, we adopted an interdisciplinary approach to select our datasets. This approach involved a combination of expert-driven evaluations, based on a participation process with experts on forest fires and forest management, and a scientific framework to ensure the inclusion of a maximum number of relevant indicators, resulting in a reliable database for a thorough assessment of Priority Management Zones (Tàbara et al., 2003). The utilization of the MAUT framework in this study facilitated the achievement of our established goals, in alignment with the defined requirements (Roe, 2012). Its

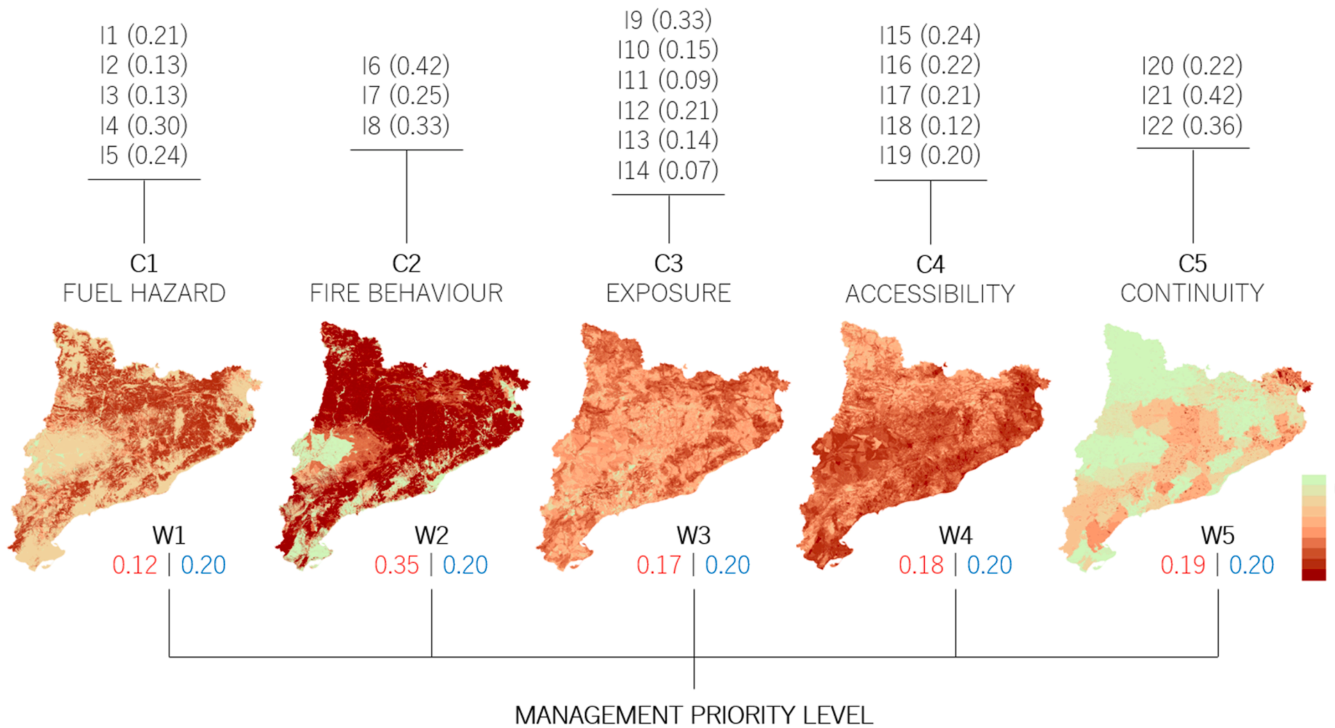

Fig. 4. Schematic design of the modelling process with applied indicator and criteria weights and cartographic representation of the criteria. Red weights correspond to Approach 1 (participatory evaluation), blue weights correspond to Approach 2 (equal weights assignation).

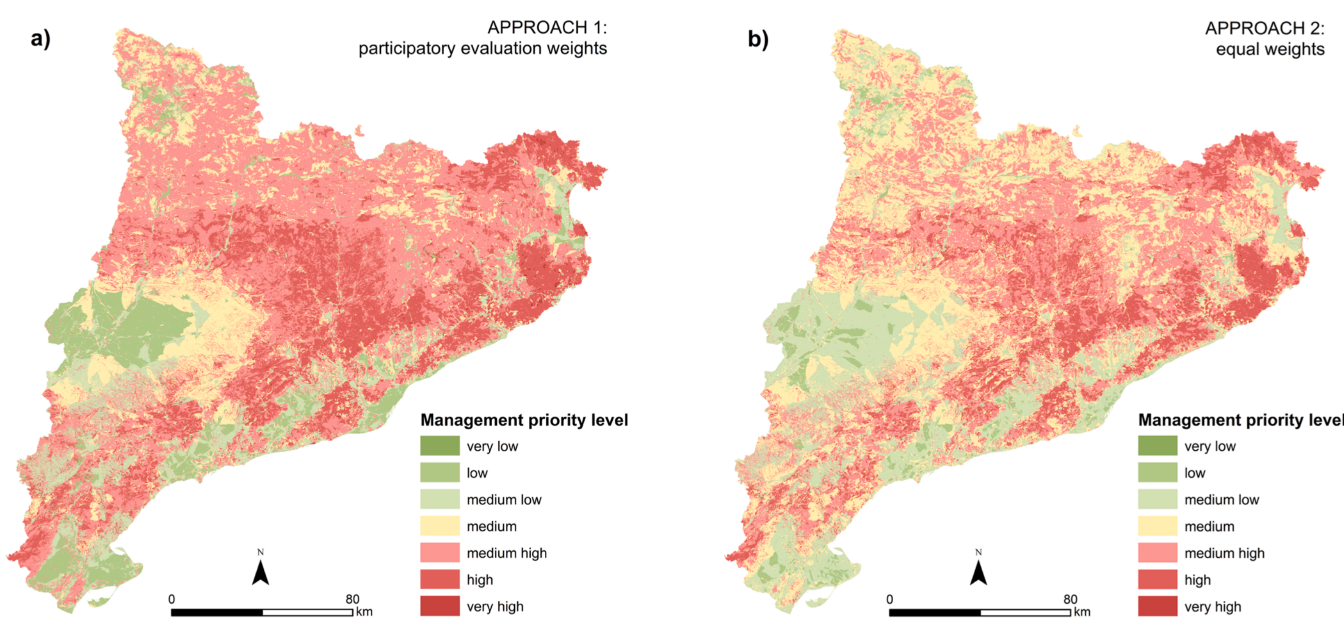

Fig. 5. Cartographic representation of management priority levels using two different criteria weight sets: a) Approach 1 – expert evaluation weights; b) Approach 2 – equal weights.

methodological flexibility effectively supported analyses geared towards decision-making. This allowed us to fulfil the objective of our study, ensuring its applicability in future applications.

Drawing on expert knowledge ground experience, participatory evaluation played a crucial role in the spatial modelling process. Beyond aiding in the establishment of indicators, it held significant importance in assigning weights, both at the individual indicator level and for criteria as a whole (Yathish et al., 2019; Perera et al., 2014; González et al., 2007). To gauge the impact of altering the relative importance of each established criterion on the assessment of Priority Management Zones, our study employed two distinct approaches. The first approach relied on expert evaluation of criteria, with their relative importance determined by respective weights. In contrast, the second approach allocated equal importance to all defined criteria, omitting expert evaluation. As demonstrated earlier, these approaches yielded markedly different outcomes, assigning varying levels of management priority to the same spatial units. The notable distinction lies in the allocation of the high-priority category. Under the equal weights approach, this category encompasses 7.98% of the study area. In contrast, when assessed through participatory evaluation, the same class extends to cover

20.69% of the area. This significantly expands the portion of the area necessitating prioritized management actions. Such disparities can substantially impact decision-making concerning Priority Management Zones, potentially leading to the misguided allocation of management strategies aimed at preventing big forest fires. Our study underscores the significance of incorporating participatory, expert-driven evaluations in topics related to fire management. This underscores the need for tools and frameworks that harmonize expert knowledge with scientific research methodologies. In such a context, the methodological foundation employed in this study, coupled with the requisite indicator dataset for a comprehensive geospatial modelling of fire susceptibility, can serve as a foundation for participatory planning and decision-making regarding big forest fires in the Mediterranean region. Unlike other studies on wildfire management prioritization that focus on a limited number of indicators tied to specific objectives (Fire Management and GIS, 1997), employ a simplified questionnaire-based participatory evaluation (Corringham et al., 2008), rely on pre-existing policy-driven priority categories (Simoncic et al., 2013) and historical data (Manaswini and Sudhakar Reddy, 2015), or enhance methodological frameworks without offering more straightforward solutions (Rodríguez Y Silva et al., 2014), our study's methodology addresses all these shortcomings. It allows for the incorporation of a diverse set of spatial variables, integrates expert-driven participatory planning, and provides solutions tailored to the specific territories.

Given the significance of how weights are assigned, as well as the choice of indicators and criteria, the interpretation of outcomes is heavily influenced by these factors (Purnomo et al., 2021). For instance, the regions of highest priority in the northeastern area are associated with relatively dry zones that experience frequent strong northward winds. These areas have a substantial presence of continuous wood fuel. Furthermore, the combination of thick understory cover and tree species with low canopy base height creates a vulnerable vertical continuity, thereby amplifying the fires risk. This region already experienced a big forest fire in 2012, burning approximately 14,000 hectares (Generalitat, 2012). The priority level is further escalated due to its high biodiversity, evident in the high percentage of protected areas. Conversely, the very high priority zones along the central coastal areas are characterized by a notable presence of semi-arid and Mediterranean shrubs, as well as pine and elevated vertical continuity forests. This landscape makes it easy for ground fires to spread to the tree crowns. Additionally, this region is densely populated, featuring numerous urbanized zones and strategic infrastructures which elevate the importance of implementing fire prevention treatment in priority areas to protect houses and people. Extensive Natura 2000 protection areas also play a role. In the high management priority zones of central continental Catalonia, the presence of continuous horizontal and vertical forest structures, coupled with dense understory cover, is a defining factor. Specific synoptic events, during which hot and dry air masses from the south affect the region, can lead to extreme fire behaviour, as witnessed in the Querlat i Miralles area in 2021 (Fitxa incendi Sta Coloma de Queralt, 2022). The prevalence of strategic management areas further elevates the priority level. Notably, this region doesn't achieve a very high management priority primarily due to its abundant water availability, setting it apart from the rest of Catalonia. The decision to assign the high priority classification to the pre-coastal range is largely driven by the high density of protected areas and an increased vertical continuity of wood fuel. A big forest fire occurred in this area in 1994 burning 7.000 ha of forested land (Los incendios forestales en España durante 1994, 1995). However, the substantial roads network, characteristic of this region, likely mitigates the very high priority level. Lastly, the medium-high and medium priority designations in the northern portion of the study area stem from its rich biodiversity and extensive network of protected areas. While the forest characteristics themselves don't inherently pose a high fire risk, the low density of roads and limited water availability required for firefighting certainly heighten the management priority level.

The primary disparity in outcomes between the two applied methodologies arises from the substantial emphasis placed on the fire behaviour criteria (C2) in Approach 1. This specific criterion draws its foundation from simulations conducted within FlamMap, which are combined with meteorological scenarios developed using the methodological framework established by a panel of experts from the Department of Climate Change and Rural Agenda within the Government of Catalonia. This framework relies on data that replicate extreme conditions of relative humidity, temperature, and wind speed required to simulate big forest fires (Krsnik et al., 2020). Concurrently, the indicators pertaining to fire extinguishment (C4) are derived from data illustrating the factors that influence the firefighting capacity to suppress the fire. In Approach 1, due to the comparatively reduced weight attributed to the C4 criteria, its values are notably lower than those of C2. Consequently, the model postulates that a fire, simulated solely based on extreme values, cannot be easily suppressed. As a result, it assigns high levels of management priority. As a solution, a more comprehensive set of outcomes could be achieved by conducting fire behaviour simulations using less extreme scenarios. This approach would facilitate better alignment with the remaining criteria. Alternatively, there's the option of re-evaluating the assigned weights, taking into account that the fire behaviour criteria are exclusively founded on extreme events. By that, a more equitable distribution of weights among the criteria would be established, seeking a balance in the assessment process.

In any scenario, the main goal of this study was to establish and parameterise indicators and criteria for prioritising areas where silvicultural treatments should be implemented to prevent large forest fires. We also wanted to demonstrate how spatial modelling and MAUT analysis can help to allocate different levels of priority management zones. Additionally, we wanted to see how changing the relative importance of different criteria affects the outcomes. Having noted this, conducting thorough participatory analyses that carefully examine how all the criteria relate to each other and how they affect the assignment of weights is something to be explored in future research. As a result, after identifying the areas where management priorities are needed, appropriate strategies for managing those areas should be also determined.

The main strength of our research lies in the participatory-planning-based co-design of a comprehensive methodological framework that enables territory- and solution-oriented management to prevent large forest fires. Drawing on expert knowledge, rules for such a framework were established, considering all relevant variables. The fact that local experts and stakeholders participate in the co-design of the utility functions and the weights used in the MAUT analysis increases results acceptance. A novelty in the approach for prioritizing forest management zones for preventing large forest fires is the inclusion of criteria related to the facilitation of suppression efforts, which is an aspect not very commonly used in Gonzalez-Olabarria et al. (2019).

A complete database for Catalonia (NE Spain) was created, making it the first of its kind and purpose in the region. While the database is only applicable in Catalonia, the established methodological framework (e.g., defined criteria, indicators, and rules) can be applied in numerous study areas. Our integrated interdisciplinary approach provides subjectivity in problem analysis, avoiding any type of interest-oriented decisions, and the utilization of existing and known tools and principles makes the framework's applicability easy and simple. For these reasons, we consider the presented methodological framework as the first step towards objective, comprehensive, and territory-oriented management of large forest fires.

5. Conclusions

This study aimed to define and parameterize indicators and criteria for prioritizing forest management areas to prevent large forest fires in Catalonia. In total, 22 indicators were defined, grouped into 5 criteria. Spatial modelling and the MAUT analysis were conducted to assess fire susceptibility, forming the basis for the allocation of management priorities. Within the process, two different sets of weights were assigned to the defined criteria: one based on expert evaluation and another using equal weights. These weights describe the relative importance of each criterion in the assessment of fire susceptibility. Results show disparities between the two applied approaches, highlighting the importance of participatory planning in the assessment of priority areas where to implement silvicultural treatments for fire prevention. The applied framework is designed to facilitate the spatially oriented definition of appropriate management strategies for reducing large forest fires in the Mediterranean region.

CRediT authorship contribution statement

Goran Krsnik: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Eduard Busquets Olivé:** Data curation, Conceptualization. **Míriam Piqué Nicolau:** Writing – review & editing, Methodology, Conceptualization. **Asier Larrañaga:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **José Ángel Terés:** Writing – review & editing, Methodology, Conceptualization. **Jordi Garcia-Gonzalo:** Writing – review & editing, Funding acquisition. **José Ramón González Olabarria:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

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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