D 3.4 Atlas of hazard, vulnerability, exposure and risk predicted for six National Parks of Italy

Work Package: WP3

Work Package leader: CNR-IBE
Deliverable leader: UNIMI

NATIONAL RECOVERY AND RESILIENCE PLAN (NRRP) – MISSION 4

COMPONENT 2 INVESTMENT 1.1 – "Fund for the National Research Program and for Projects of National Interest (NRP)"

CITATION:

Malanchini L., Vacchiano G. (2026). D3.4 Atlas of hazard, vulnerability, exposure and risk predicted for six National Parks of Italy. National Recovery And Resilience Plan (NRRP) – Mission 4, Component 2 Investment 1.1 – Fund for the National Research Program and for Projects of National Interest (NRP)", Project FIRE-BOX – Essential tools for wildland fire risk management in Italy.

DISCLAIMER

Funded by the European Union and the Ministry of the University and Research. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Executive summary

This deliverable presents an advanced methodology for wildfire risk assessment in Italian National Parks, developed within the FIRE-BOX project. The proposed approach addresses key limitations of current planning frameworks by adopting a dynamic, integrated, and model-based perspective.

Risk is assessed through the combined analysis of three main components: hazard, vulnerability, and exposure. Hazard is estimated using a wildfire spread simulator, capable of modeling fire behavior under multiple climatic scenarios, thus capturing the variability of environmental conditions. Vulnerability is evaluated through a multidimensional framework that integrates naturalistic, functional, and ecological components, allowing for a more comprehensive representation of ecosystem value and response to fire. Exposure focuses on wildland–urban interface areas, highlighting the presence of human assets and infrastructures potentially affected by wildfires.

Two types of risk are identified: Functional Risk, derived from the interaction between hazard and ecosystem vulnerability, and Civil Protection Risk, resulting from the combination of hazard and human exposure. Both are assessed under best- and worst-case climatic scenarios and subsequently integrated to identify priority areas where multiple risk factors overlap.

Overall, the methodology provides a more robust and flexible tool for wildfire risk analysis, supporting decision-making processes and improving prevention and management strategies in the context of climate change and evolving landscapes.

Keywords

Wildfires; Risk; Vulnerability; National Parks

Table of contents

1. Introduction

Wildland fires are an increasingly important driver of ecological degradation, risk to people, and damage to infrastructure across southern Europe and the Mediterranean basin, where climate change, land-use change, and fuel accumulation are expected to increase both fire frequency and fire severity (Moreira et al., 2020; Forzieri et al., 2021). In Italy, wildfire governance is distributed across national, regional, and protected-area levels, and this multi-scalar institutional setting requires harmonized data, interoperable tools, and operationally useful risk assessments to support prevention, preparedness, and adaptation (Rego et al., 2010). Yet, despite substantial progress in fire science, wildfire planning in Italy still relies largely on historical occurrence patterns and on simplified empirical approaches, while spatially explicit, mechanistic systems for the prediction of fire behavior, hazard, vulnerability, and exposure remain unevenly available across territories and agencies (Xanthopoulos et al., 2012; Sullivan, 2009).

The FIRE-BOX project was conceived to address this gap through the development of a standardized and open-access wildfire risk management toolbox for Italy. The project integrates three complementary components: a national fuel characterization and mapping framework, a harmonized database of wildfire perimeters and impacts, and a modeling environment for the assessment of wildfire hazard and risk in protected areas. Within this architecture, WP3 “Risk Box” is specifically devoted to providing National Park authorities and municipalities with tools for modern and standardized wildfire prevention, fire-risk mitigation, and climate-change adaptation.

Currently, Wildfire Prevention and Suppression (AIB) planning within National Natural Parks refers to the technical manual of the Ministry for the Environment, which constitutes the main national methodological reference for the preparation of fire prevention plans. The methodology is based on risk assessment through the integration of hazard and gravity, where hazard expresses the probability of ignition and fire spread (derived from predisposing factors and past fire events), while gravity represents the potential environmental damage as a function of the naturalistic value of the territory (forest and pastoral land cover, zoning, habitats, and species of conservation interest). In a further stage of analysis, the model also introduces components related to vegetation vulnerability and expected impact, through integration with fire behavior parameters.

However, the methodological approach proposed by the current guidelines presents several structural limitations. First, analyses are based on a predominantly static approach in which hazard conditions are derived from locally based predisposing conditions and historical series, without accounting for the dynamic variability of climatic conditions and the effects these have on fire behavior. Another limiting aspect of the methodology is related to the indicators used to calculate the potential damage produced by wildfires, which focus on the naturalistic component without considering a range of ecosystem services provided by natural ecosystems that are becoming increasingly important in spatial planning and environmental assessment.

These aspects reduce the ability of traditional models to accurately represent current and future risk conditions, especially in the context of climate change and landscape transformations.

Deliverable D3.4, *Atlas of hazard, vulnerability, exposure and risk predicted for six National Parks of Italy*, represents the synthetic cartographic and analytical output of this work package, bringing together the main territorial results generated through the project's modeling and assessment chain. The rationale of this deliverable rests on a shift from static or purely retrospective fire-risk assessments toward a process-based approach capable of representing the spatial variability of fire behavior and its consequences under current and future environmental conditions. Contemporary decision support systems can estimate fire spread and hazard by linking vegetation and land-cover properties to fire behavior models, particularly through the Rothermel framework and its derived fuel-model systems (Rothermel, 1972; Scott and Burgan, 2005; Finney, 2006). However, the application of such methods at broad scales requires harmonized fuel data, appropriate model parameterization, and computational tools able to translate weather, topography, and fuels into spatially explicit forecasts. FIRE-BOX addresses these requirements by coupling a national fuel map and fuel-model database with web-based wildfire simulation tools developed for National Park applications (Ascoli et al., 2015; Vacchiano and Ascoli, 2015; Arca et al., 2019).

In parallel, the project recognizes that wildfire risk cannot be reduced to hazard alone. Risk emerges from the interaction between the probability and intensity of fire, the ecological and functional susceptibility of affected systems, and the exposure of settlements and infrastructures, especially in wildland-urban interface areas (Moreira et al., 2020; Elia et al., 2014; D'Este et al., 2021). For this reason, the methodological framework adopted in this atlas integrates three components: hazard, vulnerability, and exposure. Hazard is derived from probabilistic fire-spread simulations and from indicators of expected fire behavior, including fireline intensity and potential propagability. Vulnerability is evaluated through a composite assessment that combines the naturalistic value of the territory, the functional importance of ecosystem services, and the ecological response capacity of vegetation and soils. Exposure is addressed with specific reference to National Park wildland-urban interfaces, where the spatial arrangement of fuels, buildings, and infrastructures influences the expected consequences of wildfire events.

This approach complements and extends the currently adopted methodology by introducing fire behavior simulation for hazard estimation, a more articulated evaluation of ecosystem vulnerability, and a specific analysis of exposure, with particular reference to wildland–urban interface (WUI) areas. The vulnerability component deserves particular attention because it extends the concept of "gravity" used in existing planning guidelines toward a broader ecological and functional interpretation of fire effects. In the draft methodology, vulnerability is articulated into a naturalistic component, based on land cover, park zoning, and protected-area designations; a functional component, focused in this first application on carbon stock; and an ecological component, represented by vegetation stability and post-fire soil erosion potential. This formulation is consistent with the project description, which identifies carbon stocks and sinks, as well as soil loss, among the key ecosystem dimensions to be assessed in protected areas, and links post-fire erosion to RUSLE-based modeling supported by spatially explicit fire-severity information and site characteristics (Gasparini and Papitto, 2022; Renard et al., 1997). In the present atlas, this framework has been adapted to the actual availability of comparable datasets across the pilot areas, with some indicators simplified where harmonized park-wide information was not available.

A further strength of the FIRE-BOX approach lies in its integration of retrospective and predictive information. The project builds on the harmonization of national wildfire perimeter data and on the enrichment of those records with fire-weather indices, fire-severity classes, and fire-emission estimates derived from remote sensing and semi-physical modeling approaches (Vitolo et al., 2020; Eidenshink et al., 2007; Key and Benson, 2006; Reinhardt and Dickinson, 2010; Chen et al., 2019). These datasets provide an empirical basis for calibrating and validating the predictive tools used in WP3. In particular, retrospective fire-severity analyses support the interpretation of modeled fire-intensity patterns, while fire-weather information derived from reanalysis products helps define the hazard conditions under which the simulations are conducted. This integration increases the credibility and operational relevance of the final atlas by connecting scenario-based mapping with observed fire dynamics in Italy.

The atlas focuses on six pilot National Parks selected to represent the broad climatic, biogeographic, and forest-context variability of Italy: Stelvio National Park and Val Grande National Park for the Alpine context, Appennino Tosco-Emiliano National Park and Pollino National Park for the Apennine context, and La Maddalena National Park and Gargano National Park for the Mediterranean context. This selection allows the project to test the transferability of a common assessment framework across markedly different fuel complexes, topographic settings, climatic regimes, and patterns of human presence. The resulting comparative perspective is central to the purpose of this deliverable, which is not only to describe risk conditions in individual parks, but also to demonstrate the applicability of a harmonized methodology for wildfire-risk assessment in protected areas at national scale.

This deliverable therefore has a double function. At the technical level, it provides a spatial synthesis of wildfire hazard, vulnerability, exposure, and resulting risk for the selected National Parks, under a transparent and replicable methodological framework. At the strategic level, it supports the transition toward more risk-informed and forward-looking fire management in Italian protected areas. The maps and analyses reported here are intended to inform the design of prevention measures, the prioritization of interventions, the protection of ecosystem services, and the identification of WUI sectors where defensive actions and land-use regulation are most needed. In this sense, the atlas contributes directly to the overarching FIRE-BOX objective of improving wildfire prevention, preparedness, and adaptation through harmonized, science-based, and operationally accessible tools for decision making in Italy.

2. Methodology

Deliverable 3.4 proposes a new methodology for risk assessment based on three components: hazard, vulnerability, and exposure (WUI). Within the document, the methodology for the assessment of vulnerability and risk is examined in detail, while the methodologies developed for hazard and exposure are described in detail, respectively, in deliverables 3.1 and 3.3.

2.1 Risk

Risk assessment was developed by distinguishing risk into two types: a risk related to natural areas (**Functional Risk**) and a risk associated with human presence (**Civil Protection Risk**).
Both types of risk were assessed starting from hazard analyses carried out through a fire behavior simulation model, the results of which were subsequently integrated with the outcomes of vulnerability analyses for Functional Risk and exposure analyses for Civil Protection Risk. Since the hazard analyses accounted for various potential climatic conditions, two hazard maps were produced (best and worst scenario for each park), and the same two scenarios were maintained in the risk analyses.
Subsequently to the calculation of the two types of risk, a map was produced by overlaying the two risk layers in order to highlight the areas where both risks exhibit a high class.

2.1.1 Functional Risk

Functional Risk was calculated by overlaying hazard analyses with vulnerability analyses. Through a 4×4 conversion matrix, all possible combinations between the two layers were considered, resulting in a classification of risk into three classes: high, medium, and low.

		Vulnerability			
		null	Low	Medium	High
Hazard	null	0	1	2	3
	Low	1	2	3	4
	Medium	2	3	4	5
	High	3	4	5	6

2.1.2 Civil Protection Risk

Civil Protection Risk was calculated by overlaying hazard analyses with Exposure analyses. Through a 4×4 conversion matrix, all possible combinations between the two layers were considered, resulting in a classification of risk into three classes: high, medium, and low.

		Exposure			
Hazard		null	Low	Medium	High
	null	0	1	2	3
	Low	1	2	3	4
	Medium	2	3	4	5
	High	3	4	5	6

2.2 Hazard

Hazard is analyzed using a wildfire spread simulator developed by CNR IBE. The simulator is capable of calculating the main characteristics of fire behavior, such as Rate of Spread and Fireline Intensity, and of estimating fire propagation under different climatic scenarios. The simulator produces 144 different scenarios for each variable, based on 16 wind directions, 3 wind speed scenarios, and 3 fuel moisture scenarios. To quantify hazard, Fireline Intensity and Propagability were used to identify areas potentially more exposed to wildfire events. Two different scenarios were defined based on the model outputs:

Climate Scenario	**Moisture scenario (%)**	**Wind speed (m/s)**
Best scenario	11 – 14 – 17 – 90	2,5
Worst scenario	3 – 6 – 9 – 60	12,5

Regarding wind direction, the results of the different scenarios were averaged in order to highlight the most affected areas. Fireline intensity and propagability were normalized between minimum and maximum values (by aggregating the values from both scenarios for each park) in order to capture site-specific variability. Subsequently, the components were reclassified into five classes of equal size (park-specific) to allow comparison between the two scenarios. The two classified indicators were then interpolated using a 5×5 conversion matrix in order to calculate hazard, classifying it into three classes (high, medium, and low).

	Propagability						
Fireline Intensity		null	Very low	Low	Medium	Hight	Very High
	null	0	1	2	3	4	5

	Very low	1	2	3	4	5	6
	Low	2	3	4	5	6	7
	Medium	3	4	5	6	7	8
	Hight	4	5	6	7	8	9
	Very high	5	6	7	8	9	10

2.3 Vulnerability

The project analyzed the vulnerability of the pilot parks by integrating the existing methodology, using an approach that considers not only the naturalistic aspects of the territory but also ecological and functional aspects. The new methodology maintains the current gravity calculation under the name of Naturalistic Component, while adding additional components that expand its evaluation. The functional component aims to extend the functional value of ecosystems by including ecosystem services such as carbon stock, recreational value, and protective functions of forest stands, in addition to those already considered in the naturalistic component (naturalistic and landscape functions). The ecological component aims to analyze the ecosystem response to fire. For the six pilot parks analyzed, the methodology was slightly modified due to the inability to identify specific layers required for the study. The complete methodology is provided below so that it can be applied in its entirety; the modifications made for the pilot parks are noted in the text.

Wildfire vulnerability

1. Naturalistic component ("gravity")
    A. Silvo-pastoral cover map
    B. Park zoning map
    C. SIC/ZSC and National reserves map
    D. Map of priority habitats and species
2. Functional component
    A. Carbon stock
    B. Direct protection forests
    C. Tourist–recreational function
3. Ecological component
    A. Stability: assessment of ecosystem resistance and resilience
    B. Degradation: soil erosion

Vulnerability is calculated by summing the three components (all classified into three vulnerability classes) and then reclassified in order to obtain three vulnerability classes:

$$Vulnerability\ [1-3] = Naturalistic[1-3] + Functional\ [1-3] + Ecological\ [1-3]$$

2.3.1 Naturalistic Component

The Naturalistic component follows the methodology already used in the current guidelines for the calculation of gravity and expresses the damage and/or negative changes caused by wildfires to the environment with which they interact. The methodology involves the overlay of the three reclassified layers, converted into raster format according to the "prevalence criterion", obtaining the classification of the gravity of each pixel through simple addition, assigning equal weight to each component. The combination of the three variables considered (silvo–pastoral cover, park zoning, SIC/ZPS and RNS) results in the naturalistic component map. The resulting score is then divided into three classes.

Naturalistic Score	Index	Naturalistic Class
0-33	1	Low
34-66	2	Medium
67-100	3	High

It was not possible to obtain a detailed map of priority habitats for all the parks analyzed; therefore, the analysis of the naturalistic component was carried out without the aforementioned information layer, and consequently the reclassification was performed using a scale from 0 to 70 instead of 0 to 100.

A - SILVO–PASTORAL COVER MAP.

To account for the different naturalistic value of the affected areas, a nominal scale has been defined, which synthetically expresses a gradient of ecological value based on the natural and landscape characteristics of vegetation formations, ranging from very low levels (5) to maximum values (25). In this case as well, if a vegetation map and/or forest type map is not available, the land use map at Level V of the Corine Land Cover classification will be used. Using this dataset, each land use category is assigned a gravity index ranging from 5 to 25 according to the table of the *Manual for the application of the AIB Plan Scheme in National Parks – 2018*

B - PARK ZONING MAP.

The different areas of the park shall be characterized according to the following naturalistic indices, ranging from 5 to 20, where a value of 20 corresponds to the highest level of gravity.

Zone	Naturalistic score
Zone A	20
Zone B	15
Zone C	10
Zone D	5
Zone 1 (if present)	15
Zone 2 (if present)	10

C - MAP OF NATURA 2000 AND RESERVES WITHIN THE NATIONAL PARK.
The presence of Sites of Community Importance (SCI), Special Areas of Conservation (SAC), and State Nature Reserves (SNR) will be quantified in terms of presence/absence according to the following:

SCI, SAC, SNR	Absent	1 present	2 presents	3 or more presents
Naturalistic index	0	10	15	25

D – MAP OF PRIORITY HABITATS AND SPECIES.
The habitats identified within the Park (priority and non-priority) and the presence of naturalistic features with priority species to be quantified will allow the assignment of severity indices ranging from 5 to 25 (25 corresponding to the highest severity), according to the following table:

	No priority species	1-5 priority species	> 5 priority species
Priority Habitats	15	20	25
Non priority habitats	10	15	20
Non habitat	5	10	15

2.3.2 Functional Component

The **functional component of vulnerability** is defined as the capacity of forest ecosystems to provide ecosystem services and their susceptibility to losing such functions following fire disturbance. The quantification of this component makes it possible to identify areas where a wildfire event would result in a significant loss of ecosystem services, thereby allowing the identification of forest formations that are most vulnerable from a functional perspective and supporting the orientation of prevention and management strategies toward the protection of the most relevant ecosystem functions.

For the pilot parks, only **carbon stock** was considered, as it was not possible to derive the indicators required to assess other ecosystem services—such as direct forest protection or recreational functions—for all pilot areas.

CARBON STOCK:
For the assessment of carbon stock, the Total Carbon Map (ISPRA, 2018) was not adopted as a reference, although it represents a reliable dataset at the national scale and is available for all National Parks.

Following the selection of the indicator, it was classified in order to identify areas with higher carbon stock and assign the appropriate vulnerability class. Thresholds were determined using the Natural Breaks method, resulting in a site-specific classification that allows for greater local accuracy.

Indicator thresholds	Carbon stock class
Parks threshold	Low
Parks threshold	Medium
Parks threshold	High

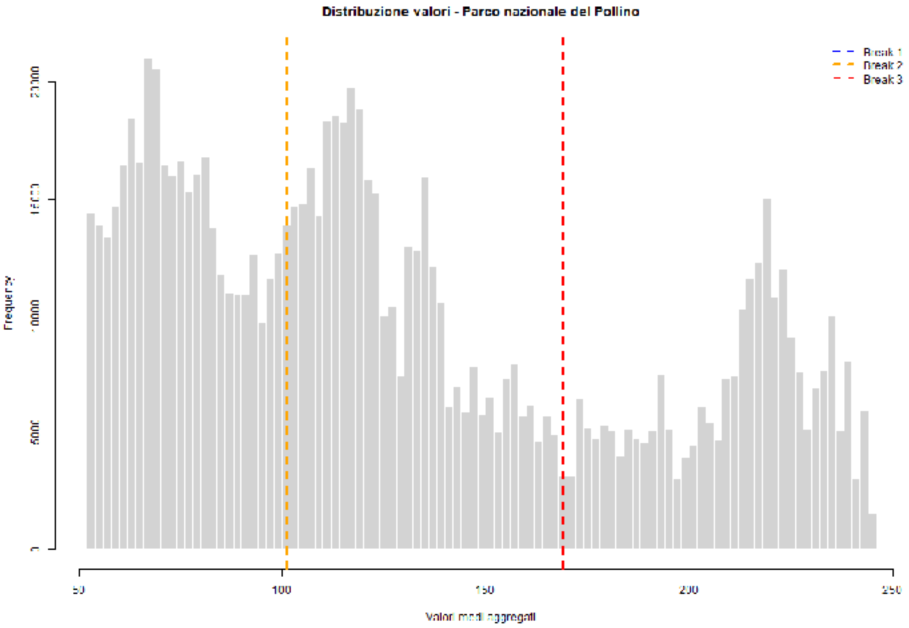

Figure 1Example of the frequency distribution of total carbon values for the Pollino National Park, showing the thresholds used in the classification.

DIRECT PROTECTION FORESTS:

The protection function of forest stands represents one of the most important ecosystem services, which requires particular attention, as damage caused by a wildfire could lead to a subsequent inability of the forest to perform its protective function against other disturbances, thereby causing further issues.

To assess this ecosystem service, various indicators can be used, which vary depending on the area being evaluated and the available information. Below are some examples of indicators that can be used:

- Map of direct protection forests produced by regional authorities or research institutions.
- “Protective” function of forests from the Forest Management Designation Map (included in Forest Management Plans).
- Map of direct protection forests against rockfall from the Rock The Alps Project. (The maps show the results of an innovative rockfall assessment methodology called ROCK-EU using harmonized criteria and objective data, and past rockfall events recorded in Alpine Space. It represents the first Alpine Space-wide harmonized rockfall risk and protection forest.)

Based on the selected indicators, a score (1–3) is assigned.

TOURISM-RECREATIONAL FUNCTION:
Within National Natural Parks, recreational activities assume a non-negligible importance. Considering the areas within parks that fulfill this function is consistent with the evaluation of the functional aspects of forests and ecosystems. To this end, the use of indicators to assess this function is proposed:

- "Tourist–recreational" function of forests from the Forest Management Designation Map (included in Forest Management Plans).
- Creation of a 100/200 m buffer area around trails, forest road networks, and points of tourist interest (such as parking areas, picnic areas, natural monuments, tourist facilities, etc.).

Based on the number and type of selected indicators, a score (1–3) is assigned.

2.3.3 *Ecological Component*

The **ecological component** evaluates the capacity of the ecosystem to resist and recover following fire disturbance. The factors influencing the ecosystem response to fire, and thus defining ecological vulnerability, can be traced back to **stability** and **degradation** (i.e., expected fire effects). The ecological component was calculated by interpolating the Stability and Degradation layers and using a conversion matrix to reclassify the result into three classes (high, medium, and low).

	Degradation				
Stability		null	Low	Medium	High
	null	0	1	2	3
	Low	1	2	3	4
	Medium	2	3	4	5
	High	3	4	5	6

STABILITY
Hierarchically, the factors considered for defining stability classes are:

- characteristics of the main woody species: passive resistance (e.g., oak stands, larch forests); resprouting ability (e.g., chestnut stands); or post-disturbance regeneration by seed (e.g., pine forests, beech forests);
- characteristics of other significant associated species.
- site-specific conditions and constraints (e.g., humid or arid environments).

Stability is therefore defined as a combination of **resistance** and **resilience** traits. Resistance is related to the physical and mechanical characteristics of individual species that enable them to withstand fire and maintain vitality. Resilience to the passage of the fire front refers to the ability of the ecosystem to restore pre-disturbance conditions. Vegetation formations can be considered resilient when, even after experiencing high-intensity fire fronts and sustaining total or partial damage to the aboveground biomass, they are able to recover rapidly through various regeneration strategies, such as vegetative resprouting.
For this purpose, a score ranging from 0 to 3 is assigned based on the stability characteristics of forest stands (national forest categories) and land use classes, according to the table below.

Forest Category Name	Stability	Stability class
Abetine	low	3
Aceri-frassineti e aceri-tiglieti	medium	2
Formazioni di altre latifoglie caducifoglie	medium	2
Abieti-faggeti e abetine miste	low	3
Alneti e altre formazioni dei suoli idrici	low	3
Atri querceti caducifogli	high	1
Betuleti, corileti e altre formazioni arboree transitorie	high	1
Castagneti	high	1
Cerreta	medium	2
Formazioni di altre conifere	medium	2
Faggete	medium	2
Formazioni ripariali	medium	2
Lariceti, lariceti-cembrete e cembrete	high	1
Leccete	high	1
Formazioni di altre latifoglie sempreverdi	medium	2
Pinete di pino montano (Mughete)	low	3
Orno-Ostrieti	high	1
Pineta d pino d'Aleppo	high	1
Pinete di pino domestico	medium	2
Peccete	low	3
Piceo-faggeti	low	3
Pinete di pino silano, loricato e altri pini sporadici	medium	2
Pinete di pino marittimo	high	1
Pinete di pino nero	medium	2
Pinete di pino silvestre	low	3
Querco-carpineti e carpineti	medium	2
Querceti di farnia	high	1
Querceti di roverella	high	1
Querceti di rovere	high	1
Sugherete	high	1
Land Use	**stability**	**Stability class**

Acque, urbano, suolo nudo	none	0
Brughiera	high	1
Canneti	high	1
Cespuglieti	medium	2
Coltivi abbandonati	medium	2
Frutteti	low	3
Impianti di arboricoltura	low	3
Noccioleti	medium	2
Praterie	high	1
Seminativi	low	3
Torbiere	high	1
Zone umide	high	1

DEGRADATION

Regarding degradation, i.e., the effects of fire on ecosystems, a synthetic indicator representing its severity is soil erosion risk. Specifically, for the quantification of soil erosion following fire disturbance, erosion was estimated under the assumption that current vegetation cover is absent, treating the entire territory as if it had just been affected by fire.

For the calculation of post-fire erosion, the Universal Soil Loss Equation (USLE) model proposed by Wischmeier was applied, assigning a value of 0.3 to the soil cover factor (C), as reported in the literature for burned areas.

$$A = R \times K \times L \times S \times C$$

A = soil loss due to water erosion ($\mathrm{t \cdot ha^{-1} \cdot year^{-1}}$)
R = rainfall erosivity ($\mathrm{MJ \cdot mm \cdot h^{-1} \cdot ha^{-1} \cdot year^{-1}}$)
K = soil erodibility ($\mathrm{t \cdot h \cdot MJ^{-1} \cdot mm^{-1}}$)
L = slope length
S = slope steepness
C = soil cover factor

The results of the equation were classified into three erosion classes. Thresholds were identified using the Natural Breaks method, based on park-specific datasets, in order to generate a classification that varies from park to park while ensuring greater local accuracy.

Erosion thresholds	**Erosion class**
Parks threshold	Low
Parks threshold	Medium
Parks threshold	High

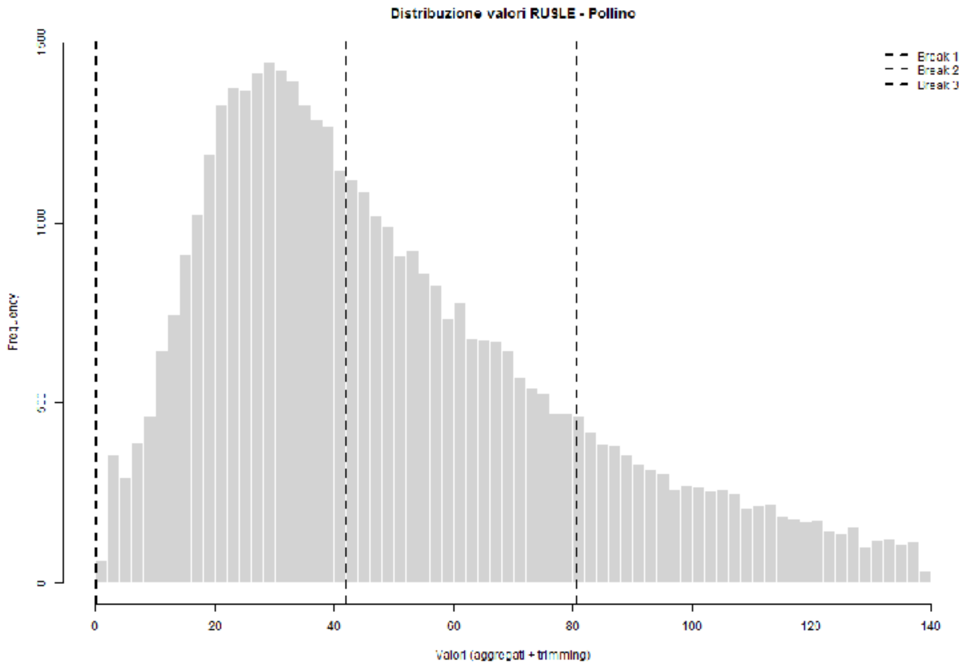

Figure 2 Frequency distribution of total carbon values for Pollino NP, including the thresholds used for classification

2.4. Exposure

Exposure quantifies the level of wildfire exposure in wildland–urban interface (WUI) areas. The methodology used for its mapping is described in Deliverable 3.3.

3. Results

3.1. Hazard

The analysis carried out using the new hazard methodology produced the following risk maps under two climate scenarios.

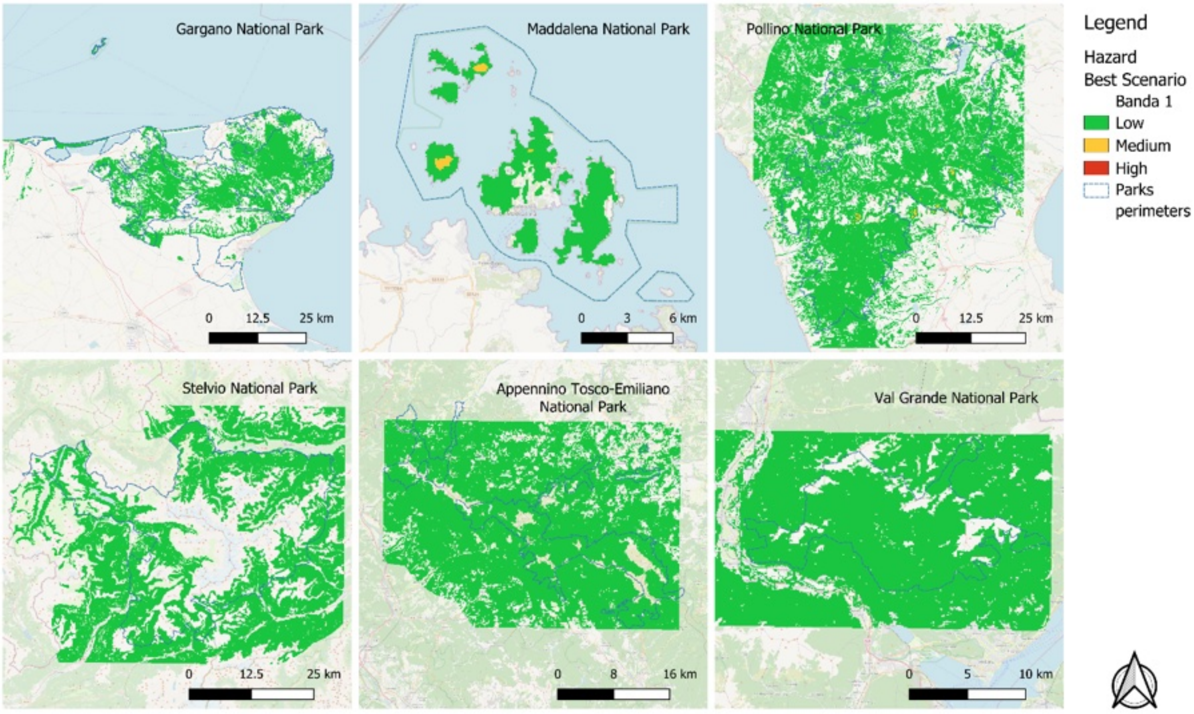

Figure 3 Best Scenario Hazard Maps for the six National Parks analyzed

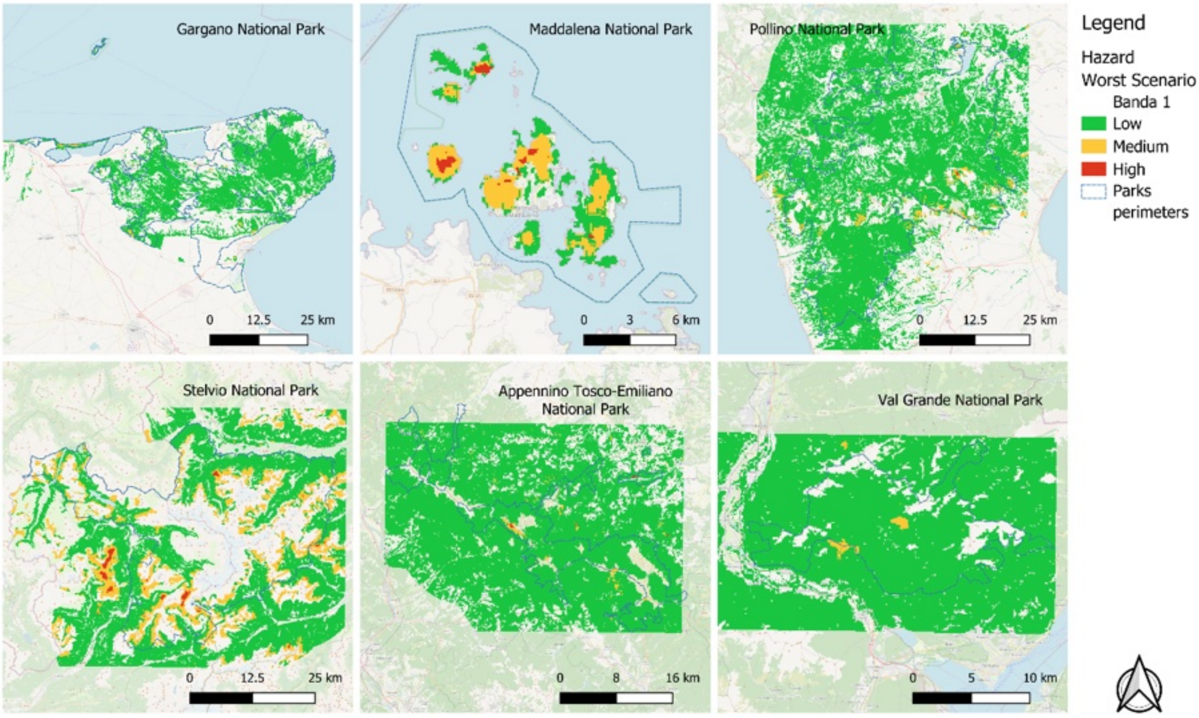

Figure 4 Worst Scenario Hazard Maps for the six National Parks analyzed

3.2. Vulnerability

The new methodology produced a set of intermediate vulnerability maps that allows for a more comprehensive assessment of wildfire vulnerability, depending on the aspect being analyzed (functional or ecological). Below is the map of overall vulnerability for the six pilot parks analyzed, with a 10 m resolution used for wildfire risk assessment.

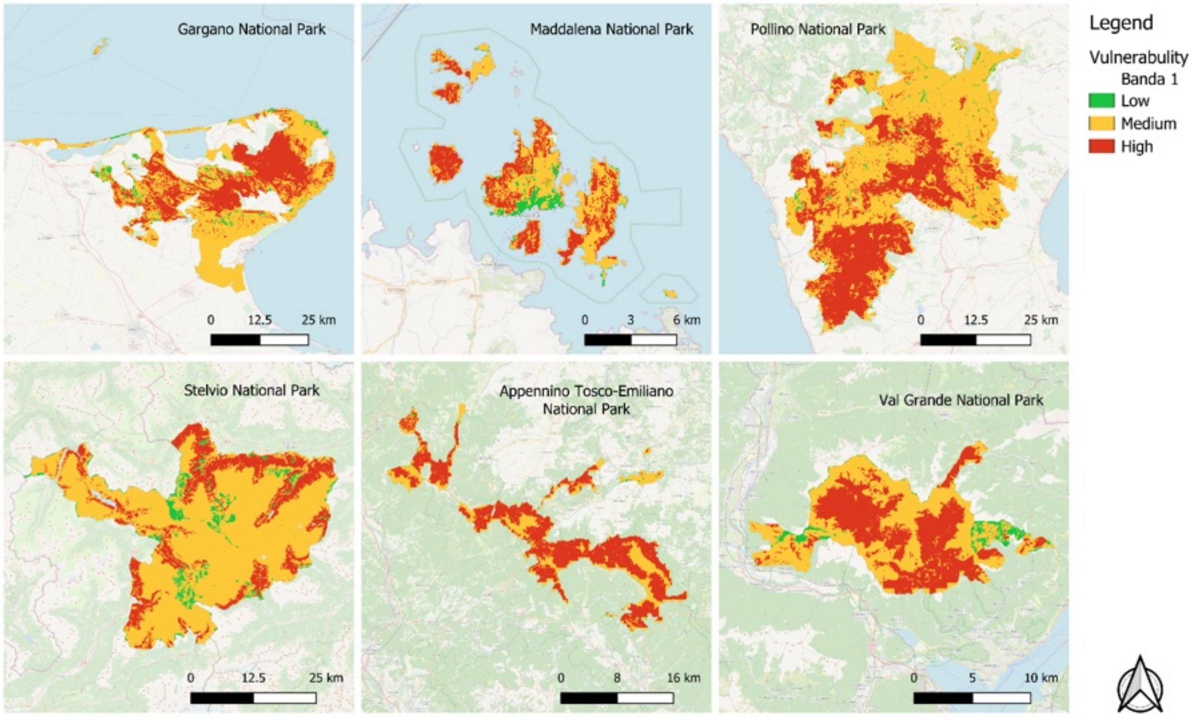

Figure 5 Vulnerability Maps for the six National Parks analyzed

Table 1 Proportion of surface area for each vulnerability class

National Park	**Vulnerability class area (%)**		
	Low	**Medium**	**High**
Gargano	3.29	58.45	38.26
Maddalena	7.98	53.54	38.48
Pollino	1.26	61.23	37.51
Stelvio	4.74	73.65	21.62
Tosco-Emiliano	0.57	36.27	63.16
Val Grande	4.27	51.15	44.57

2.4 Risk

The result of the two Risk analysis is shown in the following images. In figures 6 and 7 is shown the Functional Risk, while in figures 8 and 9 is shown the Anthropic risk.

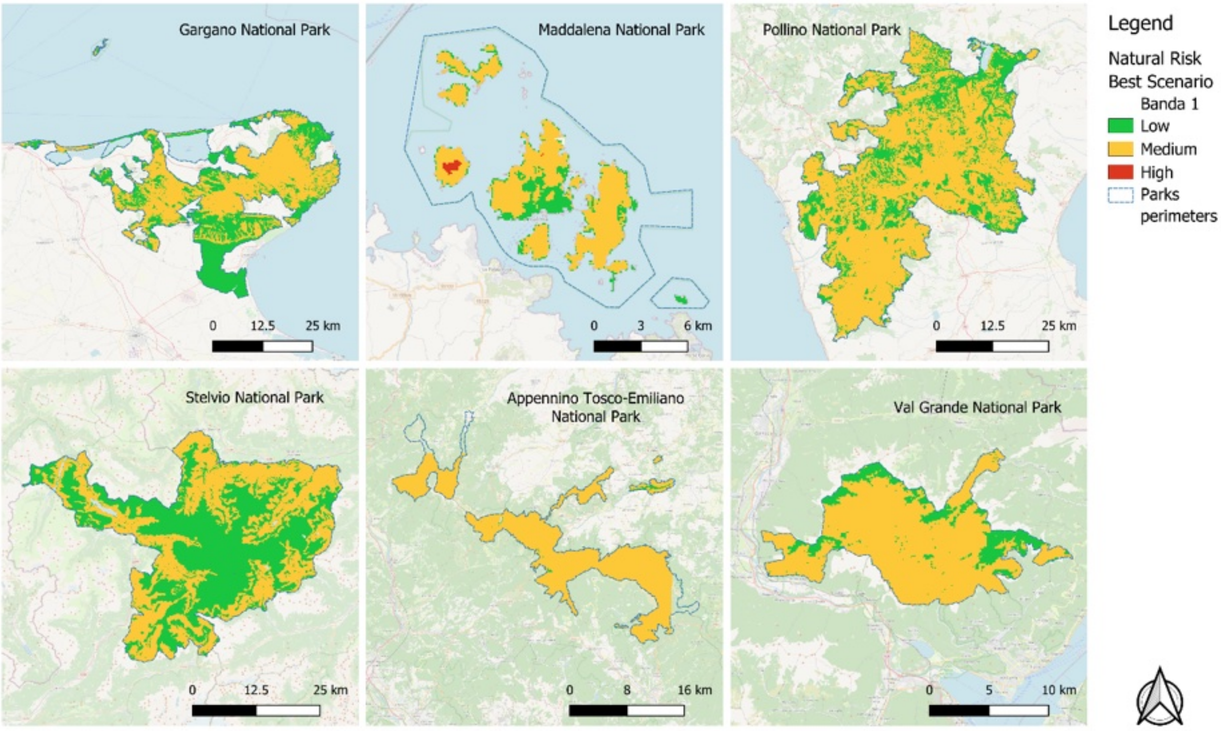

Figure 6 Best Scenario Functional Risk Maps for the six National Parks analyzed

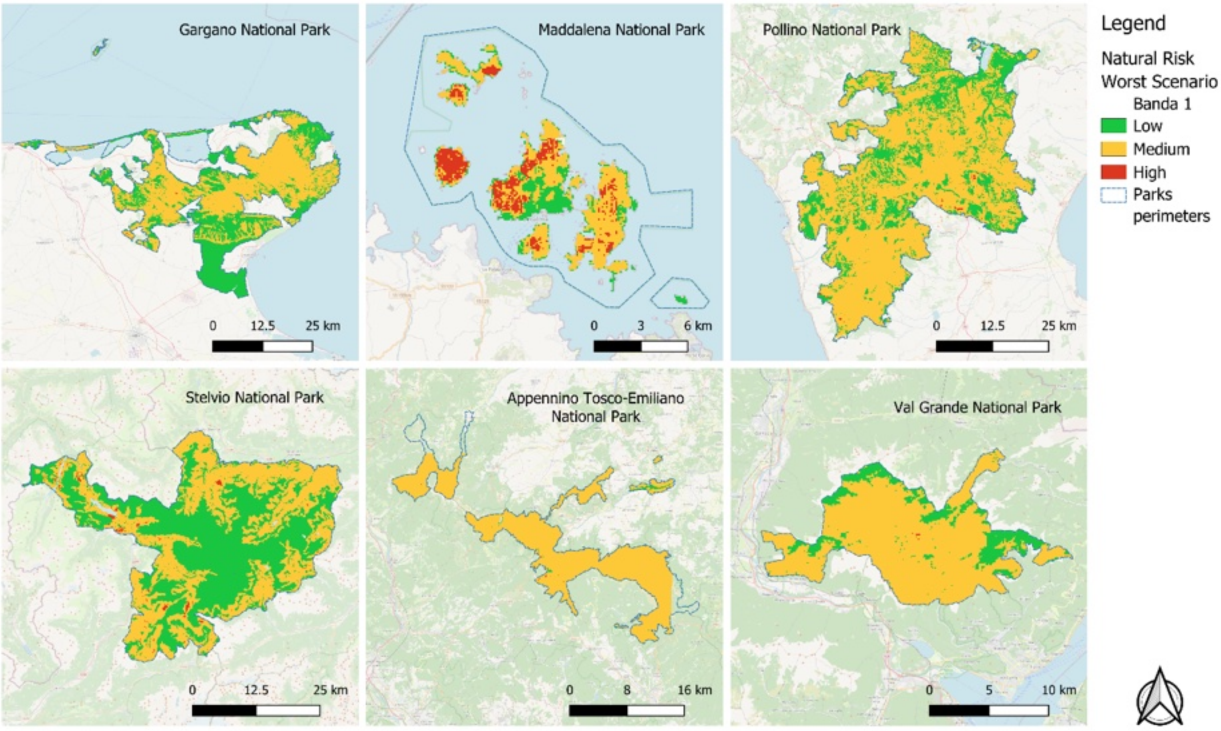

Figure 7 Worst Scenario Functional Risk Maps for the six National Parks analyzed

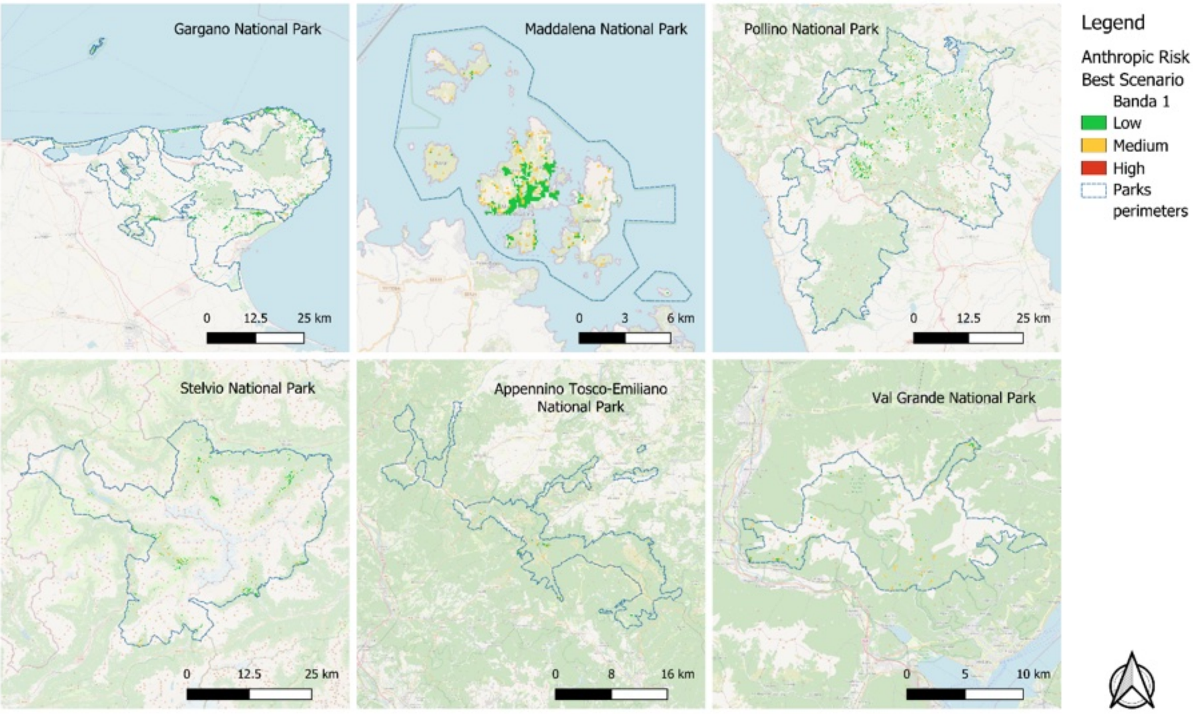

Figure 8 Best Scenario Anthropic Risk Maps for the six National Parks analyzed

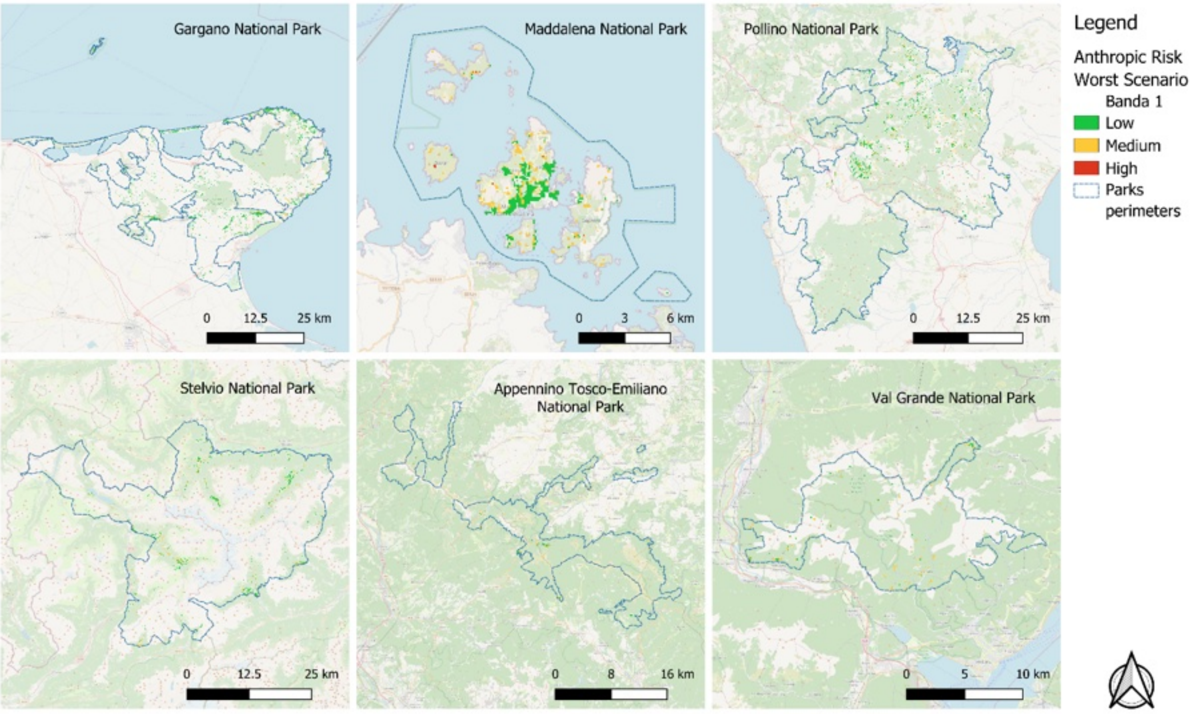

Figure 9 Worst Scenario Anthropic Risk Maps for the six National Parks analyzed

To capture both risks in a single total risk map, Figures 10 and 11 show the maps obtained by overlaying the two risks and reclassifying them into three classes, for the best case and worst case scenarios, respectively.

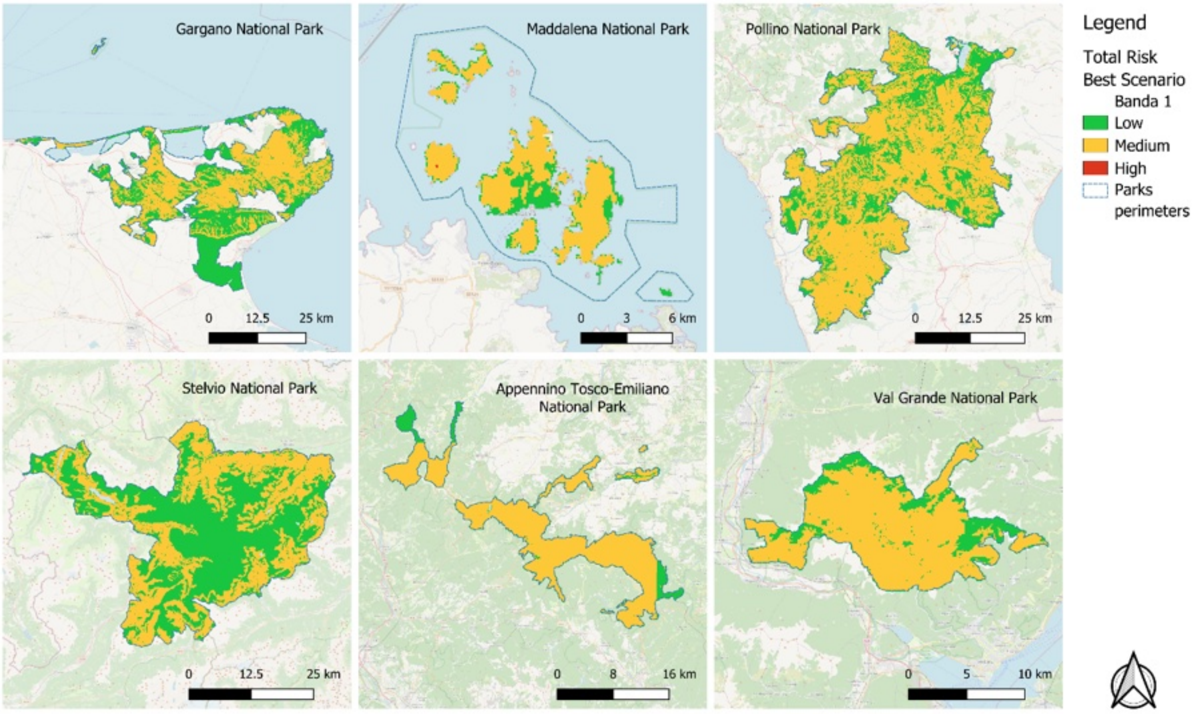

Figure 10 Bestt Scenario Total Risk Maps for the six National Parks analyzed

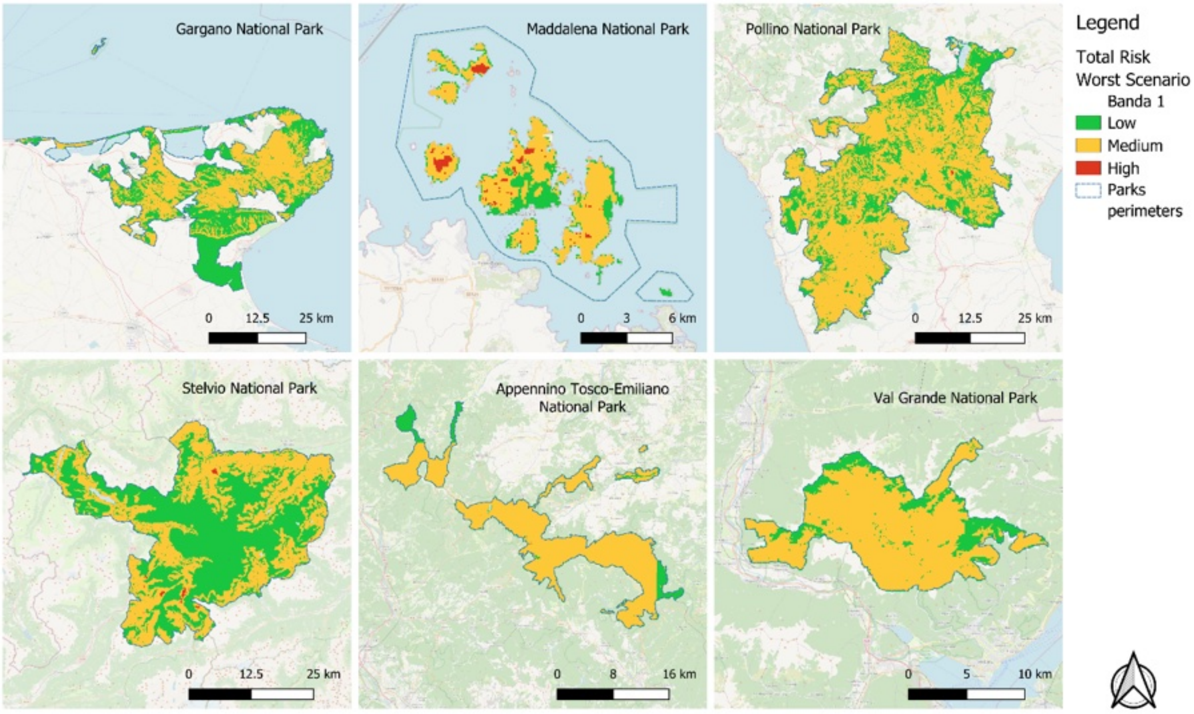

Figure 11 Worst Scenario Total Risk Maps for the six National Parks analyzed

4. Discussion

The proposed methodology represents an evolution of the current AIB framework adopted in Italian National Parks, complementing rather than replacing it by expanding its analytical capabilities. In the traditional model, risk is defined through the integration of hazard and gravity, where hazard derives from predisposing factors and historical fire data, while gravity expresses the potential environmental damage as a function of the naturalistic value of the territory. This approach ensures consistency and operational applicability in planning; however, it is largely static and therefore limited in its ability to represent climatic variability and the ongoing evolution of territorial systems.

The FIRE-BOX methodology introduces a dynamic and model-based approach to hazard estimation, relying on wildfire spread simulations under different climatic scenarios. This allows overcoming the limitations associated with the exclusive use of historical data and improves the representation of potential fire conditions. At the same time, the concept of gravity is expanded into the broader notion of vulnerability, articulated into naturalistic, functional, and ecological components. This shift makes it possible to incorporate not only the intrinsic ecological value of ecosystems, but also ecosystem services and their response capacity to fire disturbance, providing a more comprehensive assessment of potential impacts. An additional innovative element is the explicit inclusion of exposure, particularly with regard to wildland–urban interface areas, enabling the distinction between Functional Risk and risk affecting human assets.

Overall, the transition from a model based on hazard and gravity to one structured around hazard, vulnerability, and exposure results in a more comprehensive and flexible representation of wildfire risk. Nevertheless, the two methodologies should be considered complementary: the AIB framework remains a consolidated reference for operational planning, while the proposed approach provides an advanced decision-support tool, particularly relevant in the context of climate change and landscape transformation.

Analyzing the results of Hazard, Vulnerability, and Risk for the six parks considered, several considerations emerge regarding the developed methodology. The use of the simulation model developed within WP3 allows for a detailed analysis of potential fire behavior, making it possible to evaluate a wide range of climatic conditions and moving beyond a purely historical approach. To integrate these analyses into the risk assessment framework, it was necessary to derive an index from the simulation outputs to classify hazard levels and enable their aggregation with vulnerability analyses. The classification methodology adopted, together with the nature of the input data, tends to group most areas into lower hazard classes, while assigning higher classes only to areas characterized by very high values.

Conversely, the vulnerability assessment methodology tends to group most areas into medium or high classes, in line with the selection of indicators. The lack of some of the data layers originally предусмотред by the methodology reduced the number of variables included in the analysis; expanding these indicators in the future could further modify the classification of the parks.

The risk map, obtained by overlaying the previous two layers, classifies most of the park areas within the medium risk class, while clearly highlighting the areas at higher risk. These results are consistent with the previous analyses and with the structure of the methodology, as the areas at highest risk correspond to those where both vulnerability and potential hazard are high. This behavior highlights how the methodology is particularly effective in identifying critical areas, while tending to reduce variability within intermediate classes, an aspect that could be further refined through a calibration of the classification criteria.

References

Arca B, Pellizzaro G, Casula M, Duce P, Salis M, Spano D. A web-based wildfire simulator for operational applications. Int J Wildland Fire. 2019;28:99-112.

Ascoli D, Vacchiano G, Maringer J, Bovio G, Conedera M. Building Rothermel fire behavior fuel models by genetic algorithm optimization. Int J Wildland Fire. 2015;24(3):317-28.

Ascoli D, Vacchiano G, Scarpa C, Arca B, Barbati A, Elia M, et al. Harmonized dataset of surface fuels under Alpine, temperate and Mediterranean conditions in Italy: a synthesis supporting fire management. iForest. 2020;13(6):513-22.

Bertani R, Bovio G, Conedera M, Ascoli D, Elia M, Lovreglio R, et al. Manuale per l'applicazione dello schema di piano A.I.B. nei Parchi Nazionali - 2018. Roma: Ministero dell'Ambiente e della Tutela del Territorio e del Mare; 2018.

Chen J, Anderson K, Pavlovic R, Moran MD, Beaulieu PA, Davignon D, et al. The FireWork v2.0 air quality forecast system with biomass burning emissions from the Canadian Forest Fire Emissions Prediction System v2.03. Geosci Model Dev. 2019;12(7):3283-310.

D'Este M, Elia M, Giannico V, Spano G, Lafortezza R, Sanesi G. The wildland-urban interface map of Italy: a nationwide dataset for wildfire risk management. Data Brief. 2021;38:107427.

Eidenshink J, Schwind B, Brewer K, Zhu ZL, Quayle B, Howard S. A project for monitoring trends in burn severity. Fire Ecol. 2007;3(1):3-21.

Elia M, Lovreglio R, Ranieri NA, Sanesi G, Lafortezza R. A streamlined approach for the spatial allocation of fuel removals in wildland-urban interfaces. Landsc Ecol. 2014;29(10):1771-84.

Finney MA. An overview of FlamMap fire modeling capabilities. In: Andrews PL, Butler BW, compilers. Fuels management: how to measure success. Proceedings RMRS-P-41. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station; 2006. p. 213-20.

Forzieri G, Miralles DG, Cescatti A, Li W, Alkama R, Bloom AA, et al. Emergent vulnerability to climate-driven disturbances in European forests. Nat Commun. 2021;12:1081.

Gasparini P, Papitto G. The Italian Forest Inventory in Brief. In: Italian National Forest Inventory: methods and results of the third survey. Dordrecht: Springer; 2022. p. 1-15.

Key CH, Benson NC. Landscape assessment. In: Lutes DC, Keane RE, Caratti JF, Key CH, Benson NC, Sutherland S, Gangi LJ, editors. FIREMON: Fire effects monitoring and inventory system. Gen Tech Rep RMRS-GTR-164-CD. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station; 2006. p. 1-55.

Moreira F, Ascoli D, Safford H, Adams MA, Moreno JM, Pereira JMC, et al. Wildfire management in Mediterranean-type regions: paradigm change needed. Environ Res Lett. 2020;15(1):011001.

Rego F, Rigolot E, Fernandes P, Montiel C, Silva J. Towards integrated fire management. Joensuu: European Forest Institute; 2010.

Reinhardt ED, Dickinson MB. First-order fire effects models for land management: overview and issues. Fire Ecol. 2010;6(1):131-42.

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Washington (DC): United States Government Printing Office; 1997.

Rothermel RC. A mathematical model for predicting fire spread in wildland fuels. Ogden (UT): USDA Forest Service, Intermountain Forest and Range Experiment Station; 1972.

Scott JH, Burgan RE. Standard fire behavior fuel models: a comprehensive set for use with Rothermel’s surface fire spread model. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station; 2005.

Sullivan AL. Wildland surface fire spread modeling, 1990-2007. 2: Empirical and quasi-empirical models. Int J Wildland Fire. 2009;18(4):369-86.

Vacchiano G, Ascoli D. An implementation of the Rothermel fire spread model in the R programming language. Fire Technol. 2015;51(3):523-35.

Vitolo C, Di Giuseppe F, Krzeminski B, San-Miguel-Ayanz J. ERA5-based global meteorological wildfire danger maps. Sci Data. 2020;7:216.

Xanthopoulos G, Fernandes P, Moreira F. Fire hazard and flammability of European forest types. In: Moreira F, Arianoutsou M, Corona P, De las Heras J, editors. Post-fire management and restoration of southern European forests. Dordrecht: Springer; 2012. p. 79-92.