

FIREURISK - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT

Grant Agreement Number: 101003890 **Call identifier: H2020-LC-CLA-2018-2019-2020**	
Topic:	LC-CLA-15-2020 Forest Fires risk reduction: towards an integrated fire management approach in the E.U.
Instrument:	RIA

D1.4 Report on methodological frameworks for Vulnerability assessment (D, S) in the FirEUrisk- Wiki

Deliverable Identifier:	D1.4
Deliverable Due Date:	31/03/2023
Deliverable Submission Date:	05/05/2023
Deliverable Version:	v.0.6
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Work Package:	1
Task:	1.2
Dissemination Level:	☒ PU: Public ☐ CO: Confidential, only for members of the Consortium (including the Commission Services)

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Revision History

Version	Date	Edited by	Description
0.1	27/01/2023	R. Velea, R. Laterza, ISIG	First consolidated draft with contributions from all authors
0.2	08/02/2023	All authors	Additional comments and integration to all chapters
0.3	15/02/2023	R. Velea, R. Laterza, ISIG, A. Bar-Masada, U. Pernice, B. Moreira	Additional comments and integrations
0.3	16/02/2023	S. Martino	Integration to chapter 7 (section on demonstration) and chapter 8, conclusions
0.4	07/03/2023	All authors	Integrations. Version ready for internal review process
0.5	12/04/2023	All authors	Integrations following the results of the internal review process.
0.6	28/04/2023	ISIG	Integrations following the results of the review process by Scientific Coordinator. Version submitted to final Quality check.

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Quality Control

Type	Date	Reviewed by	Approved/Comment
Internal	20/03/2023	Michaela Roberts	Comments for integration
Internal	28/03/2023	Stefan Doerr	Comments for integration
Internal	4/05/2023	Stefan Doerr	Approved

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Executive Summary

The deliverable aims to report on the different approaches to fire vulnerability assessment implemented within the framework of Task 1.2 Exposure and Vulnerability.

To this end, the report illustrates the main results of four activities within T1.2: A1.2.1 Fire exposure metrics; A1.2.2 Societal vulnerability and resilience assessment; A1.2.3 Environmental vulnerability and resilience assessment; A1.2.4 Economic impacts of fire.

Initial applications of the proposed methodologies have been implemented during the first phase of the project across the envisaged sub-tasks (i.e., activities), with different levels of maturity.

The report presents, thus, where relevant, the main highlights of these preliminary applications in different project pilot sites (PS) or at the level of the European territory (ET), with the scope of showcasing the operational approaches of the proposed methodological frameworks.

These preliminary applications as well as discussions within the involved work group, suggest that integration is a key factor for maximising a coherent approach towards fire risk assessment.

Although the ambition of proposing a framework that integrates all the described approaches goes beyond the scope of this deliverable, several considerations are made across the report, and especially in its conclusion, bearing in mind the overarching project objective of developing an integrated strategy for fire risk assessment, reduction, and adaptation.

Such preliminary considerations are driven by the feasibility and necessity for a more holistic approach in fire vulnerability and fire risk assessment.

Specifically, the deliverable aims to provide useful elements to the 'integration' tasks and work groups across the project, by reporting on the potential opportunities and limitations according to both spatial and temporal scales of implementation of the proposed framework.

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List of Acronyms

Table 1: List of Acronyms

List of Acronyms	
EC/JRC	European Commission/Joint Research Centre
ECOSTRESS	Ecological Coastal Strategies and Tools for Resilient European Societies
FAO	Food and Agriculture Organization of the United Nations
FWI	Fire Weather Index
GDP	Gross Domestic Product
GIS	Geographic Information Systems
GISCO	Geographic Information System of the Commission
HFA	Hyogo Framework for Action
HVRA	Highly valued resources and assets
ICA	Integrated Capitals Approach
IPCC	International Panel on Climate Change
ISI	Initial Spread Index
LMP	Land Management Practice
MOVE	Method for the Improvement of Vulnerability Assessment in Europe
MTT	Minimum Travel Time
OSM	OpenStreetMap
RESILOC	Resilient Europe and Societies by Innovating Local Communities
SACs	Special Areas of Conservation
SCIs	Sites of Community Importance
SFDR	Sendai Framework for Disaster Risk Reduction
SoVI®	Social Vulnerability Index
SWOT	Strengths Weaknesses Opportunities Threats
UNDRR	United Nations Office for Disaster Risk Reduction
WHO	World Health Organization
WUI	Wildland-Urban Interface

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1. Introduction

1.1 An overview of Task 1.2 – Exposure and Vulnerability

Task 1.2 – Exposure and Vulnerability is embedded within the broader framework of WP1 – Fire risk assessment to improve prevention, by which FirEURisk project aims at mapping in a consistent way all risk-life-cycle phases, variables, models, and methodological schemes necessary to assess wildfire risk in several temporal and spatial conditions.

According to the project work plan, WP1 is concerned with the following objectives:

- To define and validate a unique and integrated risk-based fire management approach across all phases of wildfire issues (prevention, monitoring, preparedness, response, and restoration) towards and integrated wildfire management approach.
- To identify and map the primary human drivers of fire occurrence and evolution, taking gender and demographic factors into account, to incorporate social-science knowledge with the purpose of minimising human-caused fires and strengthening societal fire resilience.
- To advance current fire risk assessment methods by incorporating the socioeconomic and ecological impacts of wildfires, considering the value of all exposed assets, in terms of biodiversity, natural capital (i.e., the natural asset) and the ecosystem services this asset provides.
- To improve fire risk modelling in wildland-urban and wildland-rural interface areas, including novel methodologies for evaluating non-natural fuel fire behaviour, tactics for reducing fuel loads, increased firefighting safety, and risk-adapted evacuation plans.
- To create a citizen-science approach that encourages local populations to participate in fire control methods that boost rural economies, promote biodiversity, and explore nature-based solutions.

All these goals are pursued within WP1 by several tasks and sub-tasks/activities concerned with the investigation of fire risk components (as illustrated by Figure 2 below), such as fire danger assessment, analyses on exposure and vulnerability, with the intent of contributing to the development of an overall integrated risk assessment to be validated by FirEURisk.

Within such a context, Task 1.2 investigated upon different approaches that support exposure and vulnerability assessments, in the effort of paving the way for an integrated fire risk assessment framework.

Specifically, the task investigated upon the two main components of wildfire risk, i.e., exposure (E) and vulnerability (V) focusing on the following four main interconnected aspects:

- Fire exposure metrics (Activity 1.2.1)
- Societal vulnerability and resilience assessment (Activity 1.2.2)
- Environmental vulnerability and resilience assessment (Activity 1.2.3)

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- Economic impacts of fire (Activity 1.2.4)

It is important to clarify that even though the above listed activities have been framed within a holistic view of both concepts of exposure and vulnerability – as reported in Chapter 2 – the resulting methodologies have been developed in parallel and implemented as standalones; they are not directly interrelated one with the other and they are presented as such throughout this report.

However, recommendations for integration of the developed methodologies, stemming from the critical discussion of their application, are gathered in Chapter 8.2, with the aim of contributing to a coherent and integrated model considering the complexity of the analysed topic.

Finally, it must be stressed that, although the ecological and economic vulnerability are mainly considered as a disturbance factors affecting in negative way the relationships between individuals and between society and nature, this report recognises that wildfires should be understood as natural processes that in most ecosystems enact ecological functions (e.g., some Scandinavian forests, or some Atlantic heathlands) (Pausas and Keeley, 2019), and provide important human benefits such as increased carbon sequestration through recurrent small fires by enhancing belowground allocation in carbon through resprouting (Pausas and Parr, 2018), alleviation of water shortages in dry years (Boisramé et al., 2017), and reduced probability of damages from catastrophic large fires (Walker et al., 2018).

1.2 Purpose of the Deliverable

This deliverable aims to report on the different approaches to fire exposure and vulnerability assessment developed and implemented within the framework of Task 1.2 – Exposure and Vulnerability.

The report is structured as a compendium of methodological approaches towards analysing specific components and dimensions of vulnerability (i.e., exposure metrics, societal vulnerability, environmental vulnerability, economic vulnerability) at different scales envisaged by the project (Pilot Sites – PS level, Demonstration Areas – DA level and European Territory – ET level).

Initial applications of the proposed methodologies have been implemented during the first phase of the project across the envisaged sub-tasks (i.e., activities), with different levels of maturity. The report presents, thus, where relevant, the main highlights of these preliminary applications in different project pilot sites (PS) or at the level of the European territory (ET), with the scope of showcasing the operational approaches of the proposed methodological frameworks. These preliminary applications as well as discussions within the involved work group, suggest that integration is a key factor for maximising a coherent approach towards fire risk assessment.

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Although the ambition of proposing a framework that integrates all the described approaches goes beyond the scope of this deliverable[1], several considerations are made across the report, and especially in its conclusion, bearing in mind the overarching project objective of developing an integrated strategy for fire risk assessment, reduction, and adaptation. Such preliminary considerations are driven by the feasibility and necessity for a more holistic approach in fire vulnerability and fire risk assessment. Specifically, the deliverable aims to provide useful elements to the 'integration' tasks and work groups across the project, by reporting on the potential opportunities and limitations according to both spatial and temporal scales of implementation of the proposed framework.

Furthermore, detailed results of the work carried out within Task 1.2 activities, including datasets and further elaborations, are included in related deliverables: D1.5 (Geodatabases and Exposure and Vulnerability products in the GIS project platform) and D1.6 (On-line methodological handbook for socio- economic assessment of fire impacts/damages). Moreover, further applications and validation activities concerning the presented methodological frameworks (especially concerning the work on Societal Vulnerability and Resilience assessment – presented in chapter 4 and Economic impact of fires – presented in chapter 7) are envisaged for the next phases of project development, in preparation to the project's demonstration activities across Pilot Sites.

Specifically, the report aims to illustrate the main results of all research activities (i.e., sub-tasks/activities) performed within the framework of Task 1.2, as follows:

- **A1.2.1 Fire exposure metrics** – developed two independent methodologies to quantify fire and smoke exposure and showcased their implementation in the Barcelona Pilot Site (PS 4-Spain) and in the Attica Pilot Site (PS5-Greece).
- **A1.2.2 Societal vulnerability and resilience assessment** – developed two assessment frameworks:
    - **Relative Social Vulnerability Indexes** – concerned with assessment of societal vulnerability at community level and focusing on Pilot Sites scale, the framework has been proposed to all Pilot Sites, and implemented with different levels of maturity especially in 3 Pilot Sites. The deliverable showcases the preliminary results achieved for PS3 (Portugal), PS4 (Spain) and PS5 (Greece). Further applications and validation of the framework are envisaged to be developed within the next phases of the project and in conjunction with demonstration activities.
    - **Definition and mapping of WUI at European level and at all Pilot Sites** – concerned with developing the first wall-to-wall map of the European WUI at a high resolution, and detailed WUI maps at the PS level.
- **A1.2.3 Environmental vulnerability and resilience assessment** – concerned with the elaboration of a quantification model for potential impacts of fires on biodiversity and post-

[1] In fact, integration issues are currently (at the time of writing) developed within the scope of T1.3 and overall WP4 activities.

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fire recovery at regional and European scales. The deliverable defines the concepts and target variables accessible at ET scale to integrate relevant ecological values potentially affected by fires and conceptually assessable for their recovery.

- **A1.2.4 Economic impacts of fire** – concerned with developing an assessment framework of wildfire economic vulnerability from the capitals approach, stemming from the analysis of literature review and already existing approaches.

Finally, Figure 1 aims to illustrate the interlinkages between WP1, activities of Task1.2 and the structure of the present deliverable, as follows:

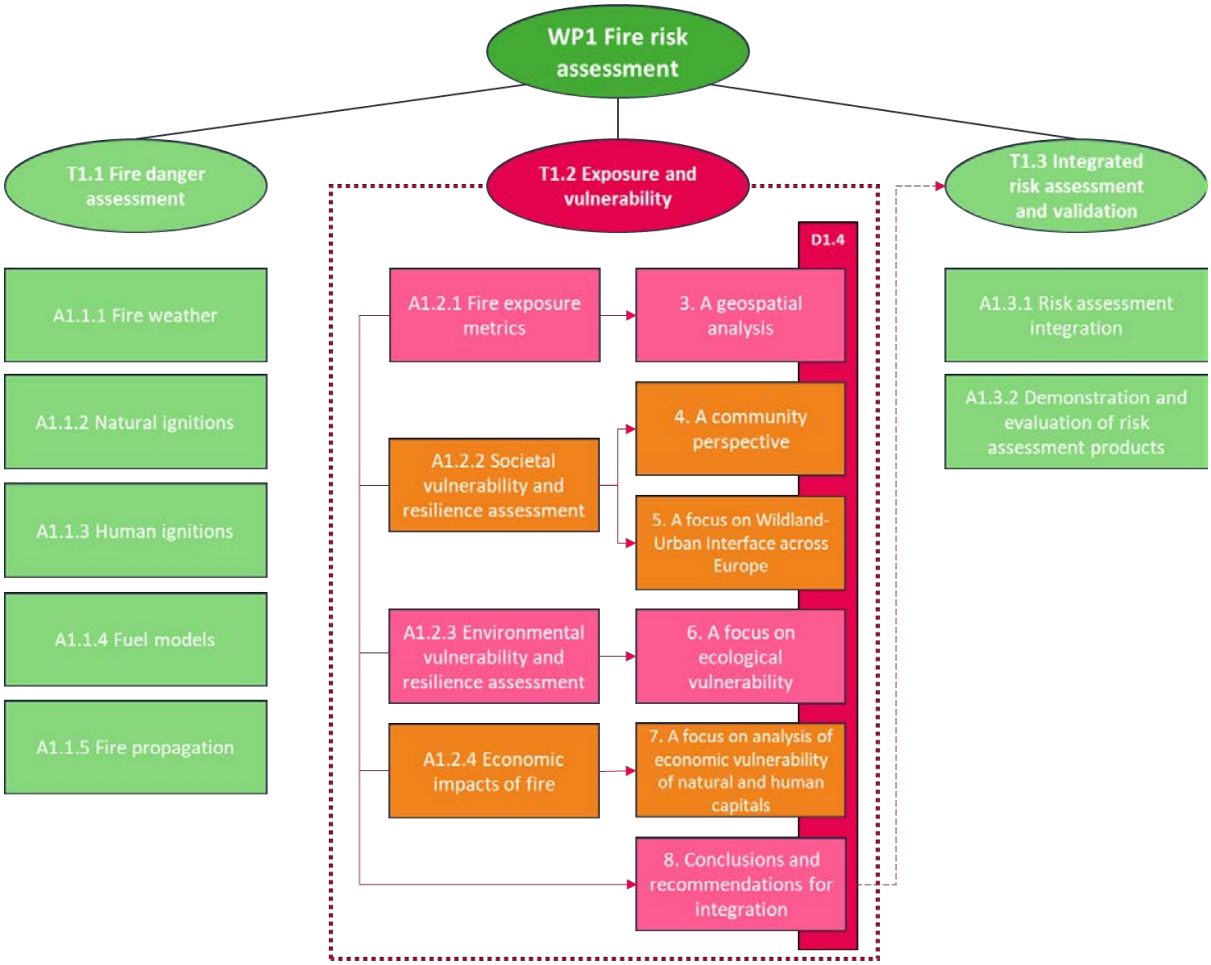


Figure 1: FirEUrisk WP1 and D1.4 structures

1.3 Performed activities

The following paragraphs aim to summarise the main activities performed with Task 1.2, as follows:

- **Coordination activities** – implemented transversally to the sub-tasks/activities, implying constant exchanges among the working group(s) members (i.e., by means of meetings, project platform, etc.). Beyond the overall coordination of the task, each sub-task/activity has animated dedicated work groups, participated by contributing partners. Moreover, within the scope of cross-cutting activities, Task 1.2 and related working group(s) have been constantly

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in contact with other tasks and WPs. Furthermore, Task 1.2 has engaged in the organisation of 3 cross-cutting meetings during the first period of the project as follows:

- The project kick-off meeting held in Coimbra in March 2022.
- An online meeting held in August 2022.
- The project plenary meeting held in Dresden in October 2022.

- **A1.2.1 Fire exposure metrics –** A review of the literature was conducted to identify the most recent approaches to quantifying fire exposure metrics using geospatial analysis. Fire risk value datasets (i.e., residential structures, road network, vegetation, Natura 2000 network, and population) were collected. The FirEUrisk methodology to evaluate the fire risk exposure of fire behaviour, smoke (i.e., atmospheric emissions and air quality), and climate was developed and applied in two FirEUrisk pilot sites.
- **A1.2.2 Societal vulnerability and resilience assessment** – the activity has been pursuing two main research streams, as follows:
  - Development of an assessment framework for the community level (focusing on the FirEUrisk Pilot Sites (PS), and especially of administrative-territorial units within the PS) and implying the development of Relative Social Vulnerability Indexes – ReSVIs. The activity envisaged: literature review, collection of qualitative data by means of interviews and focus groups with PS coordinators and relevant partners/stakeholders, collection of quantitative data from statics databases, data analysis and Indexes computation. Finally, the datasets created in this process will be made available via the FirEUrisk's data hub (reflected by D1.5).
  - Development and application of a framework supporting the definition and mapping of WUI at Pilot Sites (PS) and European Territorial (ET) levels. This process included a literature review to analyse the state-of-the-art in WUI mapping, collection of necessary geodata sets, development of a mapping methodology and its application at both PS and ET scales. Finally, the geodata sets created in this process were made available via the FirEUrisk's data hub.

  Furthermore, within the scope of this activity a focus was given to Task 1.2 associated to investigating upon frameworks of assessment of the direct effects of fire on people's lives and properties (including damages to people, domestic animals, wildlife, houses and infrastructures) and indirect effects to health by smoke produced by large fires (psychological stress, air quality). In this context, a brief literature review was performed that allowed for the collection and discussion of existing damage functions related to damage of wildfires in infrastructures, including the impacts to infrastructure failure due to wildfires and smoke exposure, per sector. The results of this activity are reported in Annex A2.
- **A1.2.3 Environmental vulnerability and resilience assessment** – The activities aimed at identifying key ecological values from a bibliographical review and integrate a conceptual resilience framework implementable from keystone processes in a processing chain using current knowledge and information available at EU scale. Activities then include a targeted

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data collection and assemblage, development of a conceptual model linking ecological values (from soil processes to vegetation growth and habitats sustaining biodiversity) and data analysis.

- **A1.2.4 Economic impacts of fire** – activities have been carried out by literature review on different capitals (natural, manufactured, human and social) and explored the potentiality and feasibility of integrations. Emphasis has been focussed on the natural, manufactured ad human capital values that can be monetised. Approaches to valuation of natural capital and ecosystem services and examples from the global north and south are provided before demonstrating how a GIS application to mapping and valuing ecosystem services at ET scale can be implemented. Suggestions on the need to overcome pure economic analysis to consider social vulnerability in a common integrated framework (Integrated Capitals Approach) are also made in the conclusions.

1.4 Structure of the Deliverable

This report represents the summary of coordinated research activities focusing on different components and dimension of fire exposure and vulnerability.

The report is thus structured so to illustrate the main proposals and findings for each of the activities, while proposing transversal considerations and interlinkages for the overall focus of the project of developing an integrated framework for wildfires risk assessment and management.

To this end,

- **Chapter 1 – Introduces** Task 1.2, purposes, performed activities, and overall structure of the framework, as well as highlighting ethical considerations.
- **Chapter 2 – Illustrates the Methodological considerations on Exposure and Vulnerability** – as the wider conceptual framework of reference concerned with the study of exposure and vulnerability.
- **Chapters 3 to 7** – illustrate the results of the research activities under focus and follow a similar structure, introducing for each topic: the conceptual framework of reference for the activity, the proposed methodology and achieved preliminary results.
    - **Chapter 3 – Fire exposure metrics** – this chapter describes a methodological framework for fire exposure metrics estimations and geospatial analysis.
    - **Chapter 4 – Societal vulnerability and resilience assessment** - A community perspective - this chapter presents the framework and application of the RESVI – Relative Social Vulnerability Index.
    - **Chapter 5 – Societal vulnerability and resilience assessment** – A focus on defining and mapping the Wildland-Urban Interface across Europe.
    - **Chapter 6 – Environmental vulnerability and resilience assessment**.
    - **Chapter 7 – Economic impacts of fire** – A Focus on Analysis of Economic Vulnerability of Natural and Human Capitals.

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- **Chapter 8** – **Summarises the results and proposes recommendations for integration,** as a legacy for tasks and WPs within the project concerned with integration aspects.
- **Chapter 9** – **References** – clustered for each chapter.

The report comprises also the following Annexes:

- **Annex A1**: A122 – Society Vulnerability and resilience assessment: ReSVI Elaboration illustrates further details on the procedure adopted to calculate the ReSVI for 3 out of 5 Pilot Site areas, as well as the results of the Index calculation.
- **Annex A2**: A122 – Damage functions review provides an overview on the methodologies to assess the direct effects of fire on sensitive infrastructures (electricity, transportation, buildings, water system) by applying a damage function-based approach.
- **Annex B**: A124 – Economic impacts of fires: Selection of Papers from the Literature Review on Economic Impacts of Fire provides the full bibliography upon which the review presented in Chapter 7 is based.
- **Annex C**: A124 – Methods for valuing and mapping agricultural values at the European Territory scale combines different layers of analysis in order to assess the agricultural values with a standardised methodology to be applied across the European Territory, taking into account forest land values, olive grove values, vineyard values, and livestock values.

1.5 Ethics considerations

All research activities contributing to the elaboration of this deliverable have been carried out in compliance with Regulation (EU) 2016/679/GDPR and 2002/58/EC Directive on privacy and electronic communications[2].

The elaboration of the present deliverable was based on both secondary and primary data, as follows:

- **Secondary data** – collected within the framework of the desk research activities, such as review and analysis of literature, statistical databases, etc.
- **Primary data** – collected via interviews and focus groups with relevant partners (i.e., interviews with Pilot Sites coordinators for assessment of proxy relevance – A1.2.2 within the scope of ReSVI).

Secondary Data is understood as all the data that have already been collected through primary sources and made readily available for further research purposes, in online repositories and public libraries. For D1.4 the analysed secondary data did not include personal data and did not require any special treatment.

[2] https://eur-lex.europa.eu/eli/reg/2016/679/oj

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For what concerns the Primary Data, the collection process was designed in full accordance with GDPR and overall FirEURisk Research Ethics, Legal and Societal Management framework (Task 7.3; D7.1 and D7.2).

Moreover, it must be stressed that interviews were conducted only with members of project partners and consisted in exchanges on the relevance and availability of statistical data coming from open sources.

To this end, given the parties involved and the topics discussed, and in compliance with the FirEURisk Research Ethics, Legal and Societal Management framework (Task 7.3; D7.1 and D7.2), it was agreed that the ethical framework under which the interviews were carried out was represented by the project Grant Agreement.

Personal data gathered through interviews were reduced to minimum and consisted in:

- Name of participants – for the purpose of identification during the meeting.
- Role/position of participants within the consortium – needed for the purpose of validation of the data collection activities.

Neither of the above-mentioned personal data is mentioned nor disclosed within this report.

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2. Methodological Considerations on Exposure and Vulnerability

2.1 Fire risk components in FirEUrisk[3]

Building on previous work on risk assessment systems, FirEUrisk aims to identify main fire risk components, by investigating further, among other, on the interconnections between hazard, exposure, and vulnerability, with the overarching goal of furthering knowledge and practice beyond risk assessment and towards reduction and adaptation to future changes. To achieve such ambitions, the FirEUrisk research group proposes:

- Specific operational definitions of the main dimensions of risk considered by the project.
- An integrated strategy for fire risk assessment, reduction, and adaptation, considering the components that affect the different dimensions of risk (danger, exposure, and vulnerability) as well as different temporal and management scales.

For what concerns the working definitions of the main dimensions of risk the following, are proposed by the project:

- Danger, that is the likelihood that a fire ignites and propagates[4]. It implies the consideration of the variables associated to human and natural causes leading to a fire ignition, as well as those factors related to fire behaviour, including rate of spread, flame length, fire intensity, and severity.
- Exposure, the extent to which people, infrastructure, and other tangible human assets, as well as ecosystems could be juxtaposed with fires. The actual exposure to fire may change because of weather patterns (i.e., heatwaves) or population movements (e.g., summer holidays).
- Vulnerability, the susceptibility to potential damages caused by fires on human and ecological values. Vulnerability is determined by the initial values of burnable resources, their resilience (in terms of resistance and recovery time) and adaptation to fire. It considers potential direct and long-term impacts of fires on human communities, infrastructure, ecosystem services and ecological values.

For what concerns the effort towards the development of an integrated strategy, the project proposes the following scheme:

[3] This section is extrapolated from the internal project working paper "Conceptual scheme for project integration" elaborated by the Scientific Committee.

[4] Even though most natural hazard terminologies name this component as Hazard, Danger is widely used in the fire management community to indicate a similar concept, for instance in the US National Fire Danger Rating System (NFDRS), the Canadian Forest Fire Danger Rating System (CFFDRS) or the Australian McArthur Forest Fire Danger Index (MARK-5). The COPERNICUS emergency service also uses the term "Fire Danger Forecast" https://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-danger-forecast, even though restricted to the meteorological component.

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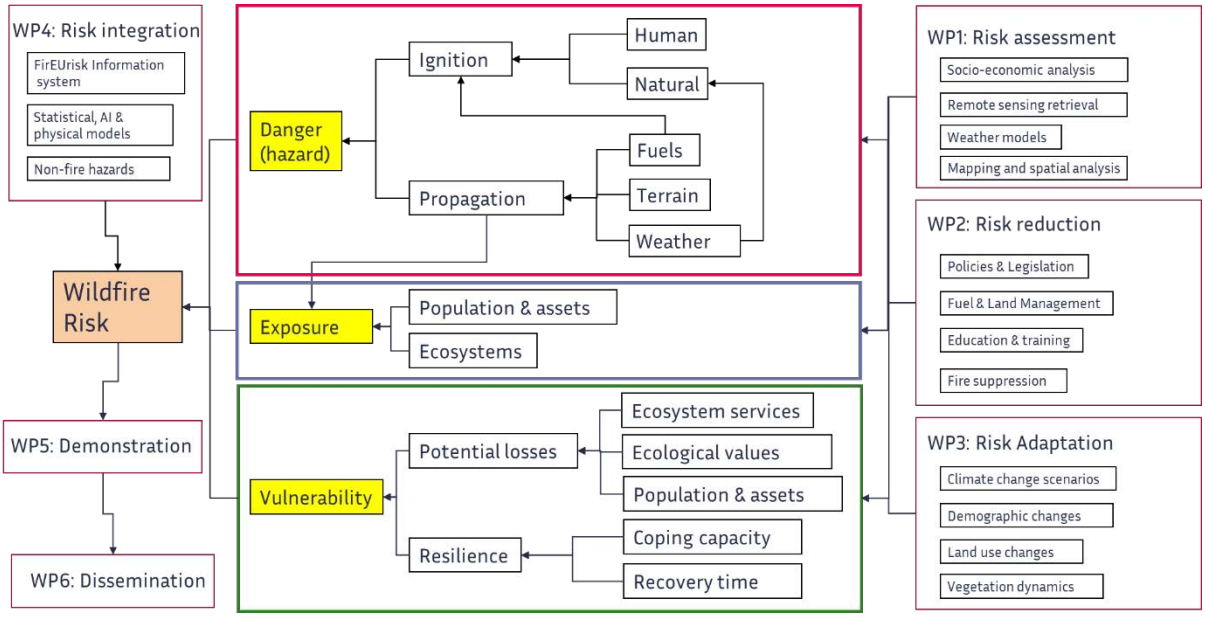


Figure 2: Conceptual integration of fire risk components within the FirEURisk project

Considering the Conceptual scheme for project integration, as already mentioned in previous paragraphs, the scope of this deliverable is that of providing useful elements to the overall 'integration activities', by:

- Exploring specific risk components (i.e., exposure and vulnerability) and proposing dedicated methodological frameworks for their assessment and analysis. And, in doing so,
- Contributing to highlighting potential opportunities and limitations regarding the spatial and temporal scales of implementation of the proposed frameworks.

The following sections aim thus to briefly introduce the main methodological considerations at the basis of the proposed and implemented frameworks for the assessment of the two fire risk components considered by the deliverable components (i.e., exposure and vulnerability).

2.2 On Exposure

Fire risk exposure information is increasingly being generated to inform wildfire planning and risk mitigation efforts around the globe (Alcasena et al., 2017, 2016; Beverly et al., 2021, 2010; Mitsopoulos et al., 2014; Thompson et al., 2016a). Exposure is defined as the extent to which a value, resource, asset, or geographic area may be subject to or encounter a potential source of harm (Thompson et al., 2016b). A potential source of harm may relate to the preconditions necessary for that process to occur (i.e., climate) or process itself (i.e., wildfire, atmospheric emissions, and smoke) (Hardy, 2005). Exposure assessments typically characterize the juxtaposition of values, such as built structures, with geographic locations where burning is possible (e.g., Beverly et al. 2010) or probable (e.g., Haas et al., 2013; Whitman et al., 2013).

The degree of damage is directly related to wildfire intensity which depends on the meteorological conditions (e.g., air temperature, wind speed, and precipitation) and the characteristics of fuel available. The greater the wildfire intensity, the greater the potential damage to residential structures,

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the road network, the Natura 2000 network, and the population (i.e., fire risk values). To prioritise risk reduction activities, it is required to know which factors can affect the community. Beyond direct exposure to flames, smoke is one of the most disturbing consequences of wildfires, with large amounts of gaseous and particulate compounds emitted to the atmosphere and strongly impacting the population's health (Amorim et al., 2016; Miranda et al., 2005; Sebastião et al., 2019). The World Health Organization (WHO), aware of the health effects of smoke from wildland fires, has already provided air quality guidelines for vegetation fire events to protect the population (WHO, 1999), particularly over the wildland-urban interface due to the highest risk of human exposure (Miranda et al., 2008). In fact, the exposure to high air pollution levels during a fire event can lead to acute health problems, which can include instantaneous rashes on the eyes, irritations in the nose and throat, and shortness of breath. These symptoms often evolve into headaches, dizziness, and nausea, lasting up to several hours. Besides these effects, respiratory and cardiovascular diseases are also common (Costa et al., 2014).

2.3 On Vulnerability

Vulnerability is defined by the UNDRR as "the propensity or predisposition of an individual, a community, infrastructure, assets or systems (including ecosystems) to be adversely affected by one or multiple hazards" (UNDRR, 2016). This definition stands at the basis of the conceptual scheme outlined by the FirEUrisk project.

Vulnerability should be understood as a very broad concept, encompassing physical, social, economic, institutional, and environmental factors, which in turn frame a variety of elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (Birkmann et al. 2013), or, in other terms, elements of sensitivity and adaptive capacities, which closely interact with the concept of exposure. More precisely, the two above mentioned terms can be defined as follows:

- **Sensitivity** or susceptibility to harm – to be understood as the extent to which the exposed elements are affected or indeed modified by the stress.
- **Adaptive capacity/coping mechanisms** – to be understood as existing or lacking skills, resources, opportunities that allow the exposed/affected elements to survive, absorb the impacts, and manage the adverse outcomes (i.e., the extent to which such capacities are developed and deployed may increase or decrease vulnerability (Fuchs & Thaler, 2018).

According to Oliveira et al. (2020), several societal factors influence vulnerability intended as the (lack of) capability to respond to a threat, thus, to mitigate or even prevent impacts caused by a hazardous event: previous experience, financial capacity, demographics, and perceived risk, among others. The authors' attempt was indeed to extend the understanding at the basis of fire risk assessment, by incorporating aspects related to exposure.

The concept of vulnerability has become very prominent in policy-driven studies, especially since the 1994 World Conference on Natural Disaster Reduction in Yokohama, in which the Strategy and Plan of Action recognised the role of vulnerability in disaster risk management. Both documents asserted that while the natural hazards causing disasters are in most cases beyond human control, vulnerability is mostly a result of human activity.

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For the United Nations Office for Disaster Risk Reduction vulnerability refers to "the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard" (UNISDR Terminology, 2017). It is possible to start assessing vulnerability by the adequate estimation and quantification of potential losses and consequences of the hazard to all assets at risk; however, the appraisal of vulnerability cannot be limited to this aspect.

Currently, disaster management practices take vulnerability into consideration mostly as a component of risk, together with hazard and exposure. Although such frameworks acknowledge the undeniable importance of vulnerability, it is important to note that “the concept (of vulnerability) is slowly finding its way into disaster management strategies” (Prior & al., 2017, p. 5).

Usually, vulnerability seems to be viewed more structurally (i.e., physically), rather than holistically, as advocated in this research and the larger FirEURisk project framework[5]. As a result, civil protection agencies and disaster management professionals tend to concentrate their risk analysis and mapping efforts on the identification of structural vulnerabilities, which are frequently linked to hazard identification and exposure (Prior & al., 2017).

Vulnerability has attracted growing attention in disaster studies and related fields, both in academic research and policy-driven studies: the high degree of diversity in its definition led to numerous attempts to build analytical frameworks for its analysis. Vulnerability has been assessed and measured in a variety of ways, including vulnerability curves, vulnerability matrixes, and spatialised through Geographic Information Systems (GIS) maps.

Using indicators has been the most often used strategy for assessing vulnerability. Indicators embed, implicitly or explicitly, goals for reducing vulnerability (or increasing resilience) to natural hazards (Fuchs & Thaler, 2018).

In recent years, vulnerability has been linked, in both academic and policy-driven research, to yet another difficult-to-define concept: resilience. Resilience has become predominant over vulnerability both in policy and in practice. This was owing in part to a lack of definitional clarity for vulnerability, ambiguities that have aided in the refining of the term resilience. Furthermore, when compared to vulnerability and its negative connotation (i.e., link with a condition of lack, or a downside), it indicates that the positive tone associated with resilience (i.e., taking actions to reduce impacts) helps explain its wider appeal and dissemination (Cutter, 2018).

The international agreement on the Hyogo Framework for Action (HFA) in Kobe, Japan in 2005 marked a gradual shift in policy from disaster vulnerability reduction to disaster resilience enhancement (Cutter, 2018). The two major reorientations consequently to that agreement were the following:

- A change in terminology, with the word "natural disasters" being replaced by simply disasters or, in some circumstances, natural hazards. The term "natural" next to "disaster" conveys the

[5] According to the Grant Agreement (p. 2), “FirEURisk will (a) model socio-economic issues and human activity influencing fire ignition, vulnerability and exposure, (b) evaluate the impact of National and EU policies on land use change, rural economy and development, in context of expected future fire regime changes, and (c) consider potential cascading effects linked to wildfire situations”.

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impression that disasters are natural occurrences for which humans can do little more than prepare and respond, rather than reducing vulnerability and building resilience, which should be the focus of risk reduction and management policies (Briceño, 2015). In this instance, authorities can blame the natural causes of the phenomena. Disasters, on the other hand, are human-centred occurrences caused by the interrelation and interaction of natural and human or social processes (ibidem).

- An increasing traction of the concept of resilience, as a means of reducing risk and ensuring a safer future.[6.]

More recently, resilience has enhanced its characteristic of umbrella term, often even replaced "risk" when defining a holistic concept, whereas vulnerability has remained stagnant and has been used more in the context of risk assessments than as a policy or strategic term (Fekete & Montz, 2018).

It must be stressed, however, that within the FirEUrisk project, resilience is considered as a component of Vulnerability (ref. Figure 2). Moreover, vulnerability and resilience are examined within the FirEUrisk framework from a systemic/holistic perspective, similar to the approach proposed by the EC/Conceptual JRC's Framework[7], which claims that resilience is context-dependent and thus must be examined within its multidimensional system of refences (i.e. ecological, social, economic, and political) (Manca, Benczur, & Giovannini, 2017).

To summarise, no matter what words are used to define vulnerability, there are some common elements[8]. Vulnerability includes elements of sensitivity and adaptive capacities, which must be assessed at the local level, considering the unique characteristics of the research/action setting. The following chapters of this report are built upon this definition and reflect the various components of vulnerability as described above.

[6] The HFA featured resilience in the subtitle of its major report, "Building the Resilience of Nations and Communities to Disasters" (UNISDR, 2005). Moreover, the Global Platform meeting in Sendai, Japan, in 2015, produced the Sendai Framework for Disaster Risk Reduction (SFDRR) – a commitment to advance disaster risk reduction and building resilience, through focused priorities for action. The targets and metrics used to assess concordance with the SFDRR currently drive the contemporary discussions on the linkages between vulnerability and resilience at global scales.

[7] Illustrated within the Report Building a Scientific Narrative Towards a More Resilient EU Society, JRC Science for policy report, 2017.

[8] In fact, among these, Adger (2006) confirms the three elements presented above, as follows: the stress to which a system (human or physical) is exposed, its sensitivity and its adaptive capacities. In this sense, the IPCC (Field, Barros, Stocker, & Dahe, 2012) define vulnerability as "the propensity or predisposition to be adversely affected […] that encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt."

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3. Fire Exposure Metrics – A Geospatial Analysis[9]

This section proposes a methodology to quantify the fire exposure potential (i.e., climate, fire behavior and smoke) of the fire exposed related values (i.e., population, biodiversity, ecosystem services, and infrastructures) by revising the current methods and tailoring it into the "Exposure" component of the FirEUrisk project. The mapping products detailed below contribute to the deliverables and serve as inputs to analyse the fire exposure at the project pilot sites within WP1.2.1 of FirEUrisk.

3.1Conceptual framework – An Introduction to Fire Exposure Metrics

During the last several decades, there has been rapid growth in housing in and near forest areas in many countries worldwide (Mitsopoulos et al., 2014). Wildfires can have significant negative impacts on buildings, infrastructure, and on the concentrations of people and socioeconomic activities that occur in these areas (Beverly et al., 2010). The identification of areas where wildland fires can spread in the built environment (i.e., surroundings constructed by people and used to stage human activities) is critically important for setting priorities for prevention, preparedness, and mitigation activities aimed at minimizing negative fire impacts (Alcasena et al., 2017; Beverly et al., 2010).

Beverly et al. (2021) developed a metric of landscape fire exposure based solely on a grid cell's proximity to nearby hazardous fuel capable of transmitting fire to its location (Alberta, Canada). Alcasena et al. (2017) assessed potential wildfire economic losses and transmission to residential houses in rural communities (Juslapeña Valley, Spain). The authors used simulation modelling to map the source of wildfire exposure to communities and estimate the expected financial loss at the scale of individual structures. Alcasena et al. (2016) developed a method to assess the wildfire exposure for highly valued resources and assets (HVRA), as well as the identification of likely areas of large fire initiation and spread (Navarra, Spain). The method employed a pixel-based LiDAR canopy fuel characterization that uses the minimum travel time (MTT) algorithm to model burn probability (fire likelihood estimate), conditional flame length (fire intensity estimate), and fire size.

3.2 Methodology for Fire Exposure Metrics in FirEUrisk

Within FirEUrisk research activities, the methodology to quantify the fire exposure potential was based on the juxtaposition of fire exposed related values (i.e., residential structures, road network, vegetation and animals' diversity, Natura 2000 network, and population) with the spatial distribution of fire metrics (i.e., fireline intensity, rate of spread, atmospheric emissions, and smoke). The algorithm was developed using a high-level programming language and Geographical Information Systems (GIS) methods.

[9] This chapter is based on the work and results achieved by the A1.2.1 working group and it is edited by the following authors of this deliverable: UAVR (Ana Isabel Miranda, Isabel Nunes, Hélder Relvas, and Diogo Lopes) and NCSR (Nadia Politi, Nadia Politi, Mandy Vlachogianni, Athanasios Sfetso).

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The final output – fire exposure potential (ranging from 0 to 1, see Equation 1) – was quantified using the following equation:

Equation 1: Fire Exposure Potential

$$Potential\ (-) \frac{Fire\ metrics \times Values\ at\ risk}{Max\ (Fire\ metrics \times Values\ at\ risk)}$$

Where the fire metrics are fireline intensity (kW/m), rate of spread (m/min), atmospheric emissions (ton) and smoke (µg/m^3), while values at risk are buildings (structures), road network (m), Natura 2000 network (m^2) and population (No. inhabitants). The fire metrics and the values at risk were selected based on a literature review.

3.2.1 Fire behaviour and smoke

The exposure was analysed based on gridded representations of landscapes with a spatial resolution of 100×100 m. A large set of modelled fire perimeters corresponding to more than 12,000 years or iterations using the MTT fire spread algorithm (from Activity - A1.1.5) were used to generate, for each grid cell, fireline intensity and wildfire rate of spread. The methodology to estimate atmospheric emissions per grid cell was based on fuel type, burnt area, fuel consumption, fire propagation, fire intensity, and emissions factors (by combustion phase: flaming and smouldering) (from Activity - A1.1.5). The smoke dispersion from the wildfires was estimated using a Gaussian dispersion modelling approach (from Activity - A1.1.5). Table 2**Errore. L'origine riferimento non è stata trovata.** shows detailed information about the used fire metrics.

Table 2: Fire metrics information.

Fire metrics	Unit	Definition
Fireline intensity	KW/m	The heat energy released per unit time from a one-meter-wide section of the fuel bed extending from the front to the rear of the flaming zone. Fireline intensity is a function of rate of spread and heat per unit area, and is broadly related to flame length
Rate of spread	m/min	The relative activity of a fire in extending its horizontal dimensions. It is expressed as rate of forward spread of the fire front
Atmospheric emissions	ton	Gases (i.e., methane, carbon monoxide, carbon dioxide, ammonia, nitrogen oxides, and sulphur dioxide) and particles (i.e., particles with an aerodynamic equivalent diameter less than or equal to 2.5 and 10 µm) which are released into the atmosphere from wildfires
Smoke	µg/m^3	Air quality levels resulted from the emission and dispersion of the pollutants in the atmosphere

In order to accurately identify all individual residential structures, the structure polygon centroids from the BTN25 (IGN, 2016) were used to generate a point file with residential house locations, for Spain, and in particular for PS4: Barcelona pilot site. The 1:25,000 scale BTN25 official geodatabase is a widely used spatial information resource for landscape and urban planning at the municipality level. In all, 23,633 individual residential houses were identified across the pilot site area, excluding

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industrial structures, silos, and agricultural machinery storage. Similar data could be used for other pilot sites.

The road network was obtained from the OpenStreetMap (OSM) dataset (OpenStreetMap contributors, 2022). It is a free, open geographic database updated and maintained by a community of volunteers via open collaboration. The spatial distribution of the vegetation was derived from the European Atlas (https://forest.jrc.ec.europa.eu/en/european-atlas/atlas-data-and-metadata/). These maps were produced by combining numerous and heterogeneous data collected from atlas monographs providing complete species distribution maps, from national to regional atlases, occurrence geo-databases, scientific and grey literature. The animal distribution was obtained from a bird (Fusco et al., 2021), reptiles and amphibians (Sillero et al., 2014), and mammals (https://discovermammals.org/projects/the-2nd-european-mammal-atlas/) database. The Natura 2000 – the European network of protected sites - was provided by the European Environment Agency, (administrative boundaries, and population grid data) covering the whole of Europe and is based on the official statistics from National Statistical Institutes. It presents detailed information about the used values at risk.

Table 3: Values at risk information.

Values at risk	Unit	Definition
Residential structures	No. structures	The number of residential structures and their geographical locations (point feature type)
Road network	m	The length of the main roads (e.g., motorway and residential) and their geographical location (line feature type)
Vegetation and animals' diversity	m^2	Forest species (e.g., Eucalyptus globulus and Pinus pinaster) and animals (e.g., birds, reptiles, amphibians, and mammals) spatial distribution
Natura 2000 network	m^2	Ecological network (polygon feature type) composed of sites designated under the Birds Directive (Special Protection Areas or SPAs) and the Habitats Directive (Sites of Community Importance or SCIs, and Special Areas of Conservation or SACs).
Population	No. inhabitants	Population map with a spatial resolution of 1 km^2

3.2.2 Climate

An additional methodology, to some extent preliminary as regards to the overall project developments towards integration, is introduced for fire exposure assessment, based on the calculation of Fire Weather Index (FWI) and Initial Spread Index (ISI) for extreme fire weather days. The concept of NCSRD 's methodology is to conduct a geospatial analysis of the fire exposed related values (i.e., residential structures, road network, Natura 2000 network, and population), described in the previous section 3.2.1, based on fire weather assessment and estimation of the extreme fire weather (FWI) days or ISI's days. The approach consists of the calculation of the spatial distribution of the probability of occurrence from the calculation of extreme fire weather days based on the classification of the related fire metrics (as described in Table 4), which combined with the fire exposed

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values, provides and assessment of long-term climatological wildfire exposure estimation. More specifically, the probability of occurrence is defined as the number of days with high or extreme fire danger per fire season as characterised by the indicator (FWI, ISI). The choice of the threshold is determined by the classification of FWI, or ISI values presented in Table 4, provided by EFFIS[10] and Varela et al. (2018) for the area of Greece. For the whole historical period, a unique value of probability is computed, spatially, for each area. This area could be a grid cell, a polygon represented from a number of stations etc. The sum of these features determines the potential fire exposed region and thus the layer of fire metrics. The fire exposure assessment with the geospatial representation of the potential exposed values, arises by overlapping the layer of fire metric with the layer of fire exposed values, in a GIS environment. This methodology highlights the likelihood of fire exposure that is related to fire weather danger.

Table 4: The classification of values for the FWI and its sub-component ISI.

FWI classes by EFFIS	FWI Percentiles by Varela et al. (2018)	ISI classes BY EFFIS
Very low (<5.2)	-	Very low <3.2
Low (5.2-11.2)	Low 25th percentiles	Low 3.2-5
Moderate (11.2-21.3)	Moderate 50th percentiles	Moderate 5-7.5
High (21.3-38)	High 75th percentiles	High 7.5-13.4
Very high (38-50)		Very high 13.4-30
Extreme (>=50)	Extreme 90th percentiles	Extreme >30

This methodology deals with a long-term perspective of fire exposure assessment compared to the previous methodology described in section 3.2.1. In addition, it takes into consideration only the fire weather which is linked to possible fire events and not the exposure to smoke emissions produced by large fires. Finally, the fire effects estimation on infrastructure assets depends on specific thresholds which are determined by design requirements and measurement methods of each asset for different hazards and structures, dictated by the Eurocodes in Europe. Eurocodes are a harmonised set of structural design standards of buildings and civil engineering works constructed in the European Union (EU), developed by European Committee for Standardisation over the last 30 years to cover the design of all types of structures made of steel, concrete, timber, masonry, and aluminium (http://eurocodes.jrc.ec.europa.eu/showpage.php?id=13).

3.3 Results of Fire Exposure Metrics in FirEUrisk

The developed FirEUrisk methodology was tested in two selected pilot sites. The fire exposure potential for the fire behaviour and smoke was estimated at the Barcelona pilot site (PS4) while the climatological fire risk exposure based on the selected values at risk was tested at the Greece pilot site (PS5).

[10] https://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-danger-forecast

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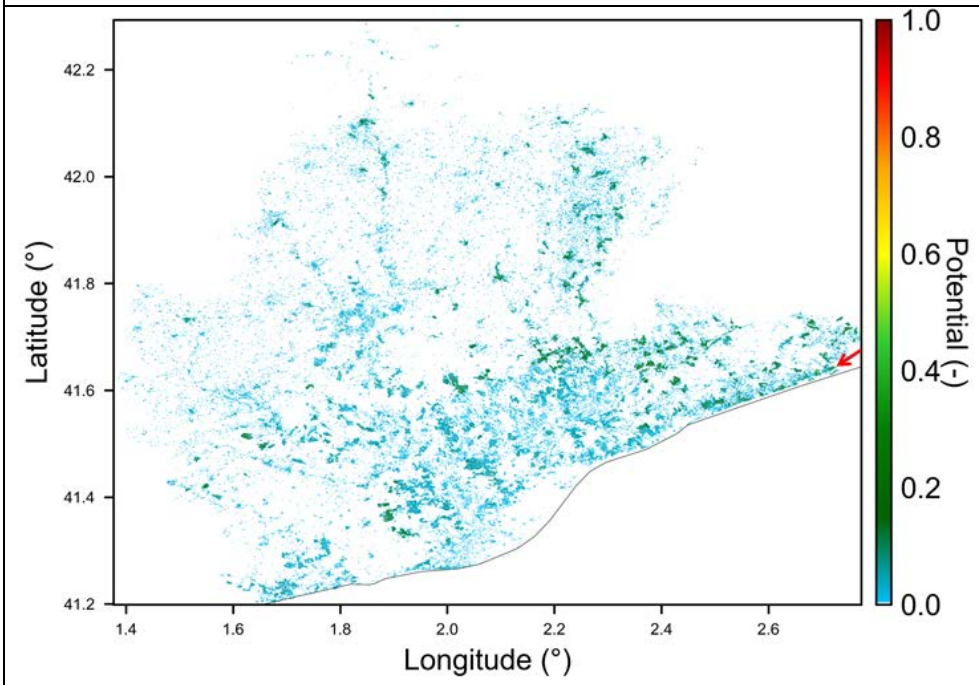
3.3.1 Results Overview

3.3.1.1 PS4: Barcelona Pilot Site

PS4 (province of Barcelona) was selected as a case study to test the developed approach. This region encompasses 7,726.36 km² and is in Northeast Spain. It has a population of 5,635,043 people, very large communities, and a growing Wildland Urban Interface (WUI) sprawling from Barcelona. More than 100,000 ha (22% of the land area) are under various nature protection figures, experiencing high touristic pressure. Figures 1 and 2 show examples of potential exposure to PM10 emissions using the following fire related values: residential structures, road network, Natura 2000 network and population. The red rows indicate the maximum fire exposure potential value (i.e., 1).

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a) Residential structures



b) Road network

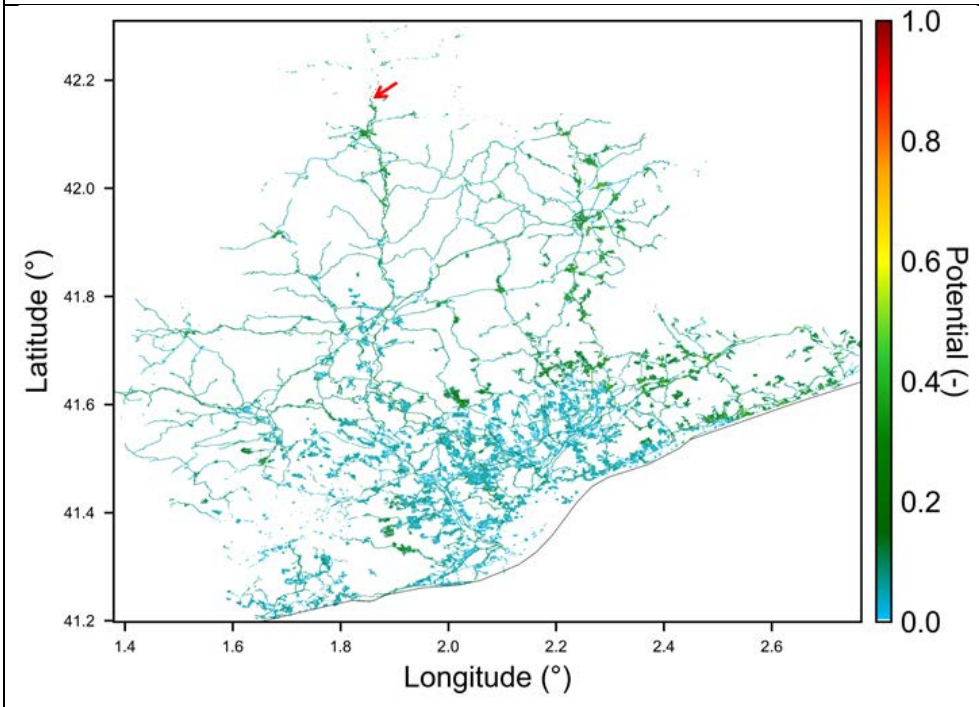
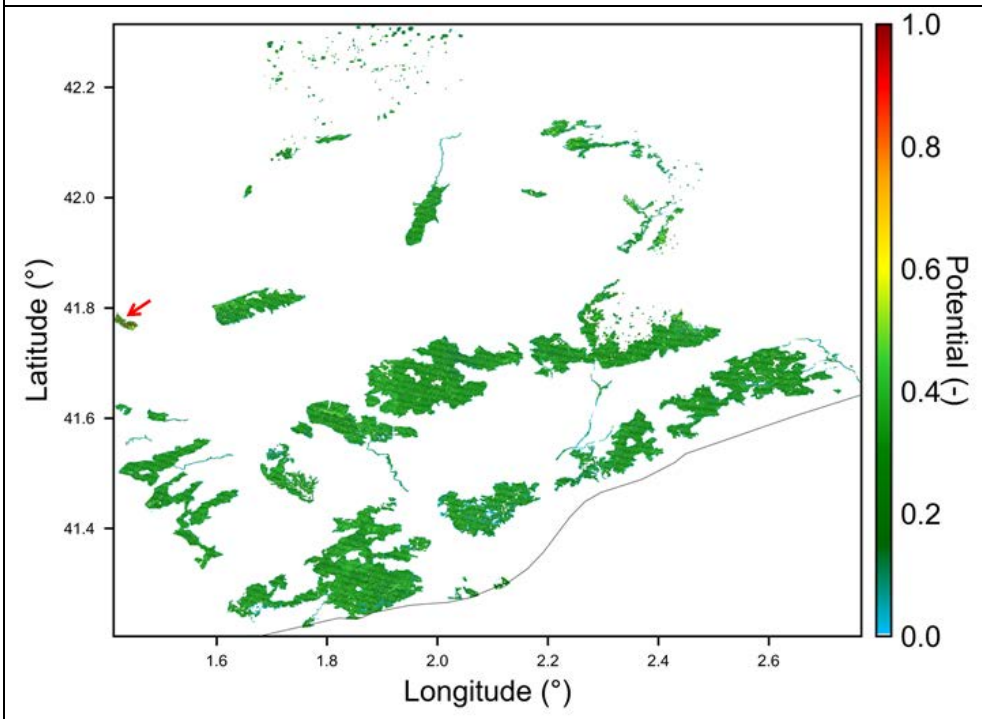


Figure 3: Maps of potential exposure to PM10 emissions: a) residential structures, b) road network

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c) Natura 2000 network



d) Population

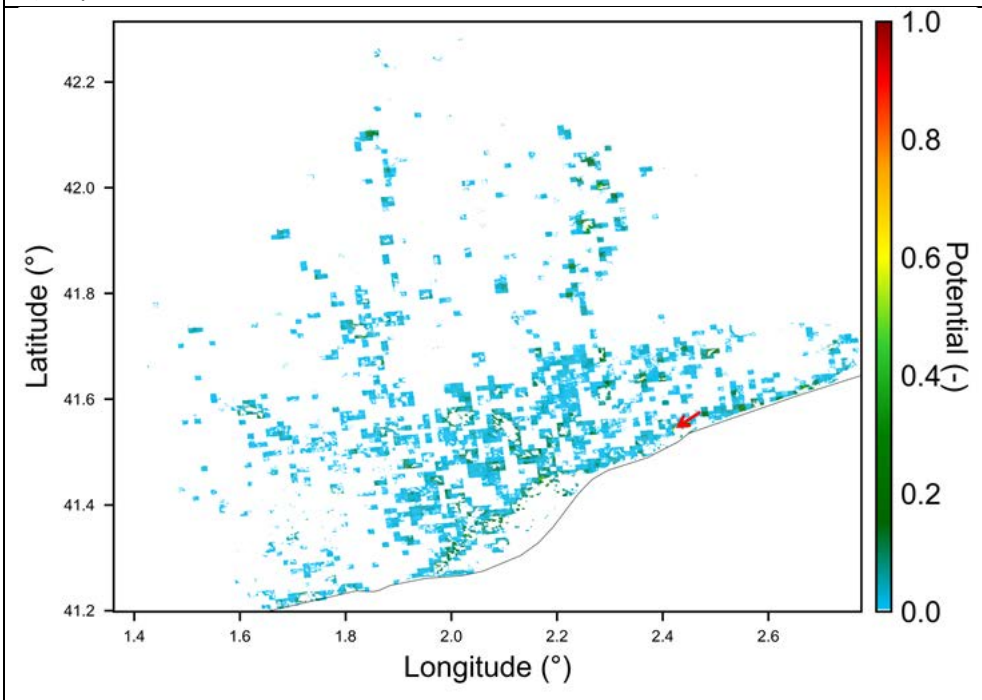


Figure 4: Maps of potential exposure to PM10 emissions: c) Natura 2000 network, and d) population

The maximum fire exposure potential to PM10 emissions was estimated in different regions depending on the considered fire related values (i.e., residential structures, road network, Natura 2000 network, and population). The fire exposure potential was on average 0.04 (STD=0.05) for residential structures, 0.09 (STD=0.09) for road network, 0.26 (STD=0.1) for Natura 2000 network, and

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0.01 (STD=0.03) for population. The highest potential exposure for the residential structures was obtained at the municipality of Santa Susanna, while for the roads, the largest value was estimated in a small village in the Cercs municipality (La Rodonella). Castellfollit de Riubregós was the region with the highest exposure potential on their Natura 2000 network (Average=0.45 and STD=0.31). It was estimated that the population could be more affected by PM10 emissions in Mataró (the capital and largest town of the Maresme municipality).

3.3.1.2 PS5: Greece pilot site

PS5 (East Attica Region) is one of the regional units of Greece and covers an area of 1,513 km^2. It is part of the region of Attica and is subdivided into 13 municipalities. Its population counts of 516,549 people (census 2021). The regional unit covers the eastern part of the urban agglomeration of Athens, and the rural area to its east.

To calculate the FWI, Greece is divided into a high spatial resolution grid consisting of 5 x 5 km^2, and the fire metric is computed for each gridded cell. Primary validated gridded variables for FWI calculation, are derived from EC-EARTH model output dynamically downscaled using WRF model appropriately set up based on previous studies (Katopodis et al., 2021, 2020; Politi et al., 2022, 2021, 2020, 2018). More specifically, the probability of occurrence is calculated for each fire season above a certain threshold (defined as an extreme value, see table 1) and during all the examined years through the historical period. The extreme fire weather days and ISI values are generated in the Activity - A1.1.1. Thus, the fire metric is the probability represented as the mean number of days above threshold based on Varela et al. (2018) approach of Percentiles classification as presented in Table 4, that considers specific physical characteristics of the study area. In the final step, for the representation with results of the potential fire exposure, the output layer of the probability and the layers of the exposure values, can be combined and presented in a GIS map for the region of interest for the estimation of fire exposure danger.

3.3.1.3 Discussion

Two methods for the calculation and the spatial distribution of exposure values were explored. Both use fire exposed related values, such as population density, but the first one crosses these exposed values with fire related metrics, while the other one is based on the exposure to fire weather extreme events. In the first case, fire exposure potential is provided using results from propagation modelling, namely propagation potential maps. In the other case, the applied method provides the likelihood of fire exposure that is related to fire weather danger.

As a first application example, high-resolution maps of the fire exposure potential at the Barcelona pilot site were presented. The obtained results allowed to identify and map potential structural (including ecological) damage and population exposure to smoke, as well as to improve prevention and preparedness planning at the WUI. These potential exposure maps can be produced crossing different fire metrics and exposed values selected taking into account particular requirements from particular stakeholders. This exposure potential method is going to be applied to other FirEURisk pilot sites and to the EU territory.

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Moreover, for the PS5 (East Attica Region) the considered fire metric was the probability of occurrence defined as the number of days with high or extreme fire danger per fire season as characterised by the indicator (FWI, ISI).

The exposure information that can be produced, and was already produced, within FirEURisk has a huge potential for the identification of expected exposure hotspots and thus for the prevention of the impacts of fire on assets and population. Furthermore, this information should be part of the integrated FirEurisk framework allowing advancing in the chain of fire risk events.

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4. Societal Vulnerability and Resilience Assessment – A Community Perspective[11]

This section proposes a methodology to assess societal vulnerability and resilience in relation to wildfires at a community level (focusing on a territorial, administrative, or statistical unit). The developed methodology, called ReSVI - Relative Societal Vulnerability Index, focuses on the analysis of the capitals interacting and constructing a local community (i.e., the unit of analysis of the framework). These capitals are represented by ReSVI through the following dimensions: Social dimension, Economic dimension, Institutional dimension, Human capital dimension and Environmental dimension[12]. For each of these, quantitative and qualitative variables have been identified so to describe the related dimensions of societal vulnerability at community level. The comparison among similar communities (territorial, administrative, or statistical units) and/or their higher administrative tiers, according to the five dimensions contribute to elaborate Relative Societal Vulnerability Index.

As it is aimed at supporting local and/or regional authorities to elaborate resilience strategies tailored at the local community level, it mainly deals with 'coping capacity' as a fire risk component defined within the Integrated Scheme of FirEUrisk project.

The ReSVI[13] methodology was developed and implemented within the Activity 1.2.2 – Societal vulnerability and resilience assessment, as a continuation of previous works focusing on community vulnerability and resilience from a multi-hazard perspective.

[11] This chapter is based on the work and results achieved by the A1.2.2 working group and it is edited by the following authors of this deliverable: ISIG (Daniele Del Bianco, Olivia Ferrari, Riccardo Laterza, Ramona Velea)

[12] It must be stressed that the vulnerability dimensions used by the ReSVI (i.e., social, economic, environmental, Human capital and institutional), as well as the selected variables (indicators and proxies) aim to capture the human aspects and overall social interaction at community level influencing societal vulnerability , and in this sense they do not overlap with the other dimensions of vulnerability explored and analysed by the other proposed methodologies in this deliverable.

[13] ISIG main work of reference: Relative Social Vulnerability Index and SWOT Analysis of Coastal Case Studies in the Upper Adriatic performed by ISIG within the Project ECOSTRESS (Ecological COastal Strategies and Tools for Resilient European SocietieS) (2013-2015), project co-financed by the European Union ECHO/SUB/2013/671461; establishment of a vulnerability assessment system, through a dedicated self-assessment tool for Local Authorities in the framework of the Project RESBA (Resilience of Barriers) (2018-2020), developed for the Municipality of Turin; analytical framework for the vulnerability analysis at Local Community level, coordinated by ISIG within the Project RESILOC (Resilient Europe and Societies by Innovating Local Communities) (2019-2022), project financed by the European Union's Horizon 2020 research and innovation programme under grant agreement No 833671; elaboration of ReSVI (Relative Social Vulnerability index) and realisation of SeAT analysis (Social Vulnerability Assessment) performed by ISIG within the project PITEM Riskgest (2019-2022), project financed in the framework of the Interreg ALCOTRA Programme; ReBuS – Resilience Building Strategies Toolkit, online manual aimed at providing public authorities with tools to assess resilience of their communities and to support planning for strategic response to emergencies, developed in 2021 by ISIG for the Council of Europe.

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4.1Conceptual framework – An Introduction to Societal Vulnerability.

This section summarises the main results of a non-exhaustive literature review carried out on definitions and approaches to the analysis of societal vulnerability.

Specifically, this section aims to:

- Provide an overview of the main approaches towards the analysis of vulnerability that have been reviewed for the purpose of this report and that represent the basis for the elaboration of the societal vulnerability and resilience assessment framework of analysis.
- Set the FirEUrisk societal vulnerability and resilience assessment in the overall framework of the project.

4.1.1 Vulnerability Across Research: a focus on Societal Vulnerability

4.1.1.1 Types of vulnerability

Vulnerability research comprises several thematic elements or types of vulnerability (e.g., social, economic, physical, institutional vulnerability).

For this section, it must be stressed that the guiding research perspective is that of societal vulnerability: both for what concerns literature and methods of analysis.

The societal vulnerability perspective is in fact encompassed by the overarching objective of the FirEUrisk project, which is to investigate socio-economic issues and human activity influencing fire ignition, vulnerability, and exposure to strengthen socio-economic and ecological resilience to fire.

Societal vulnerability is the study paradigm most associated with the concept of (community) resilience in the literature, particularly in terms of examining a community's potential to recover. The capacity to cope with and adapt to dangers is at the heart of the relationship between vulnerability and resilience. Social capital – an essential characteristic in the examination of socio-demographic character in hazard-exposed communities and in societal vulnerability studies – contains such capacities. Bourdieu (1986) defined social capital as "*the aggregate of the actual or potential resources which are linked to possession of a durable network of more or less institutionalised relationships of mutual acquaintance or recognition*". Social capital generates value by means of "*features of social organisation, such as trust, norms and networks that can improve the efficiency of society by facilitating coordinated action*" (Putnam in Prior & al., 2017, p. 6). Social capital appears thus to be closely tied to a community's adaptive capacity: daily interaction is what allows individuals to act collectively and collaborate (Adger, 2003 in Prior & al., 2017).

The methodological framework proposed by this chapter build particularly on two vulnerability classification frameworks, as follows:

- MOVE framework of (Birkmann, et al., 2013), which identifies six dimensions of vulnerability, namely, **Social, Economic, Physical, Cultural, Environmental, and Institutional.**
- Fuchs and Thaler's (2018) 4-dimensional model, composed by Physical, Economic, Institutional and Social vulnerability dimension, in which the physical dimension covers environmental variables, and the cultural dimension is treated under the social dimension.

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4.1.1.2 The Dynamic Nature of Vulnerability: Units of Analysis

A further degree of complexity to the definition of vulnerability is given by the potential interactions and relations between its inherent elements, such as:

- **Spatial scale of vulnerability** – understood as national, regional, local, or even individual**.**
- **Temporal scale of vulnerability** – before, during or after a disaster.
- **Sectors of interest** – physical system, economic system, institutional system, social system.

The connections between these elements are not always obvious in attempts to define vulnerability. The attempt to conceptualise vulnerability and its elements as a Rubik cube (first by Kienberger, 2013 and then by (Fuchs & Thaler, 2018) is a good starting point for reducing the complexity of defining vulnerability while emphasizing the necessary dynamic approach to viewing and analysing it.

When analysing vulnerability, one ordering element appears to be the so-called subject of concern, or who is vulnerable, or, better yet, what is the unit to which the vulnerability analysis applies. According to the literature, vulnerability can be defined as:

- Place (i.e., vulnerability of a locality).
- Systems (i.e., physical system, economic system, etc).
- Social groups.

A stream of influential studies has addressed vulnerability in terms of place (Cutter, Mitchell, & Scott, 2000; Cutter, 2008), referring to a locality's vulnerability (e.g., vulnerability of Georgetown). In this context, the term place emphasises both the geographical concept and the physical characteristics.

Another approach to vulnerability analysis is to consider individual and social group sensitivity by focusing on existing societal structures and processes that may determine that different socially defined groups may suffer disproportionally because of a hazard (Birkmann, et al., 2013).

For this chapter, the subject of concern, thus the unit of analysis, will be the community, understood as the territorial-administrative or statistical unit, within the FirEUrisk Pilot Sites and Demonstration Areas[14].

4.1.1.3 Relationships between Vulnerability and Resilience

This sub-section presents the findings of the literature review concerned with the current debates on the relations between the concepts of vulnerability and resilience in research concerning with community scales (of interest for the methodological framework proposed in this chapter ReSVI. The section aims to provide readers with a general overview on the matter and goes beyond the FirEUrisk conceptual and integration scheme (ref. Figure 2) according to which, resilience is considered as a component of Vulnerability.

[14] Based on the different administrative setting across the FirEUrisk territory, Pilot Sites as such may entail a 'regional' perspective integrating several specific local communities, while Demonstration Areas may be understood as local levels only.

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Although vulnerability and resilience are linked, they "*remain different approaches to understanding the response provided by systems and actors to natural hazards*" (Fekete & Montz, 2018, p. 3). As concepts, they are similarly diverse, and they belong to several paradigms, allowing for multiple definitions and measurements depending on the field and focus of the study. "*Resilience refers to the capacities of people, places, and infrastructure to, not only cope with hazards, but also the longer-term adjustment and learning processes to adapt to future threats*" (Fuchs & Thaler, 2018, p. 3) (Adger, 2000, p. 348)(Adger, 2000, p. 347)(Mancini, Salvati, Sateriano, Mancino, & Ferrara, 2012, p. 192).

Community resilience was defined in disaster management literature as "the ability of a community to prepare and plan for, absorb, recover from, and more successfully adapt to actual or potential adverse events in a timely and efficient manner including the restoration and improvement of basic functions and structures" (Cutter, Ash, & Emrich, 2014, p. 65). Therefore, resilience is a positive, desirable attribute of a community, insofar as a community that is resilient will "eventually suffer fewer losses in case of a disaster and will be able to recover more quickly" (Scherzer, Lujala, & Rød, 2019, p. 1). Or, in more sociological terms, community resilience is made of "a complex web of social interactions, characteristics and capacities that enable a community to live with the hazards they face" (Crowley Née Donovan & Elliott, 2012).

Despite being a unifying policy catchphrase and being used as a new holistic paradigm of disaster and crisis management, resilience remains rather flexible and difficult to pin down (Scherzer, Lujala, & Rød, 2019). As many authors have pointed out, this difficulty stems from the relative nature of resilience as well as the need to be specific.

Scherzer puts it succinctly: "Which entities (e.g., individuals, households, communities, cities, societies) should be resilient to which shocks (e.g., earthquakes, storms, manmade threats) at which magnitudes (e.g., everyday struggles or rare extreme events) within which boundary conditions (e.g., targeted speed and level of recovery) need to be defined for every case, every research study" (Scherzer, Lujala, & Rød, 2019, p. 3).

As illustrated in previous sections, the difficulties signalled by the concept of resilience are replicated in the case of the concept of vulnerability. In some ways, vulnerability is the inverse of resilience. In other conceptualisations, resilience and vulnerability share some elements, but each is a distinct concept, eventually complementary to one another rather than diametrically opposed.

The disaster research community has long pursued divergent paths in the study of vulnerability and resilience (Cutter, 2018; Cutter, et al., 2008). While vulnerability, as advocated primarily by Social Sciences and humanities, investigated susceptibility to harm, particularly to people and things valued, resilience was advanced by the ecological sciences in order to comprehend "*disturbances in systems and the ability of such systems to absorb "shocks," recover from them, and return back to some steady-state condition*" (Cutter, 2018).

The relationship between resilience and vulnerability is not always a straightforward linear inverse proportionality. Other possible relationships between resilience and vulnerability exist, and scholars generally distinguish four main potential combinations, as depicted by Fuchs and Thaler (2018):

- **Combination 1. High vulnerability and low resilience** – the combination refers, for example, to communities that have high social and physical vulnerability and low coping capacity to

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respond to events, where natural hazards events cause high damages towards the population and constructions (e.g., the Indian Ocean earthquake and the related tsunami in 2004, which caused major disruptions to living conditions and commerce, particularly in Indonesia, Sri Lanka, India and Thailand).

- **Combination 2. High vulnerability and high resilience** – the combination refers, for example, to local communities that demonstrate a high degree of coping capacity to respond to natural hazard events, but where the events have a tremendous impact, such as the Tohoku earthquake and the subsequent tsunami event – a severe natural disaster that occurred in north-eastern Japan on March 11, 2011, which instigated a major nuclear accident at a power station along the coast.
- **Combination 3. Low vulnerability and low resilience** – the combination refers, for example, to communities "*with a high-degree of resilience-building policies, but which fail to develop a local network system and adequate demographic* structure" (Fuchs & Thaler, 2018, p. 4). Usually this is the case with natural hazard events affecting aging communities in the Global North, such as coastal climate change affecting the area of Nova Scotia in Canada (Manuel, Rapaport, Keefe, & Krawchenko, 2015) or in Florida in the USA (Tobin, 1999).
- **Combination 4. Low vulnerability and high resilience** – the combination applies to situations in which the community is not inherently vulnerable towards natural hazard events and at the same time showing a "*high social understanding and coping capacity of the society, which can fast absorb and recover from a natural hazard event*" (Fuchs & Thaler, 2018, p. 4).

Although potentially challenging and in need of further development, the combinations extrapolated from Fuchs and Thaler (2018) may prove particularly relevant when considering analysing vulnerability and resilience frameworks at the community level for the purpose of designing integrated risk reduction strategies.

According to the literature, the factors that determine vulnerability may also contribute, to varying degrees, to the development of resilience (ECLAC, 2011). It is common for researchers to investigate concepts of vulnerability, particularly social vulnerability (Cutter, Burton, Boruff, & Shirley, 2003). Cutter later shifted to more resilience-oriented approaches in the analysis of assets of vulnerable communities (Cutter, Burton, & Emrich, 2010).

Previous work conducted in the framework of RESILOC H2020 project contributed to shape the concept of 'community resilience'. The results of that inquiry suggest that an overall assessment of 'community resilience' should consider the following features, by encompassing them in a broad perspective on the issue:

- Physical and social elements of local communities.
- Different capacities of local communities.
- Ability of the local community to adapt or transform themselves.

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- An understanding of the local community and its different actors and components as a complex system, which can be interpreted also as a combination of static (i.e., structural) and dynamic (i.e., processual) elements.

4.1.2 Measuring and Assessing Vulnerability: A Review of Different Methods and Tools Across Vulnerability Studies

The concept of measuring usually refers to the development of specific quantification tools, metrics, or indexes that can describe vulnerability phenomena, while the concept of assessment encompasses a broader range of approaches to understanding the scope of vulnerability as a complex issue.

A vulnerability assessment process might be understood as the process of identifying, investigating, quantifying, weighing, and ranking a set of vulnerabilities (or indicators designed to express vulnerability), comprehending the relationships between these vulnerabilities, and comparing them to other sets within the same system (or country, or region). A vulnerability assessment includes, among other things, listing a set of vulnerabilities, assigning value scores to them, and analysing these values in context. Both quantitative and qualitative methods, as well as a combination of both, have been used to develop vulnerability measurements. What is clear is that no one can agree on the best way to measure such a complex phenomenon (Fekete & Montz, 2018).

Various criticisms have been levelled at measurement methodologies, with the majority of these focusing on the difficulties of using indexes, issues associated with spatial and context differences, and data assessment at various scales of analysis (Barnett, Lambert, & Fry, 2008; Fekete & Montz, 2018). Comparisons have been discouraged on the grounds that vulnerability is a context-specific rather than a generic condition (Barnett, Lambert, & Fry, 2008). Another criticism focuses on the dynamic nature of the vulnerability phenomenon, which is constantly changing (Adger, 2006), which limits the use of socioeconomic indicators measured at specific points in time to predict the vulnerability of assessed communities.

4.1.2.1 Quantitative versus qualitative perspectives

When considering vulnerability analysis from a community perspective, the dynamic nature of both the phenomenon (vulnerability) and the unit of analysis (community) is critical in determining the most appropriate approach.

Quantitative methods and data can provide a static picture of a community and can help to describe and quantify the phenomenon. However, approaches to vulnerability that rely solely on quantitative data can be limiting in terms of understanding the true implications and connections of intervening factors at the community level.

Such an approach to analysis may reveal essential elements for the assessment of sensitivity-related components (e.g., quantification of the damage caused by exposure), but it may result in a limiting assessment of adaptive capacity elements, such as skills and resources. Such considerations become especially important when attempting to shift from a vulnerability to a resilience-building perspective. Although quantifying and measuring resources and skills within a community is possible, assessing them requires a deeper understanding of how they interact in the context at hand. Skills and resources

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may be deployed differently in different contexts, and in terms of assessment, even if deployed identically, they may have a different impact.[15]

Moreover, given that each community is unique, it is necessary to incorporate local knowledge and awareness into the analysis to fully understand the interactions and implications of the identified variables with the context itself.

One potential solution, especially when referring to community vulnerability, can be found through participatory approaches to vulnerability assessment (as the one entailed by the methodological framework proposed within this chapter).

4.1.2.2 The issue of relativity: the challenge of assessing community vulnerability in absolute terms

Vulnerability and resilience are both relative terms (Cutter, 2016; Fekete, 2019). The numerical values assigned to them because of assessments and measurements gain significance through comparison and ranking within a cluster of similar units of analysis. They need answers to questions like "Vulnerability to what?" "Whose vulnerability?" and "How is vulnerability measured?". Understanding vulnerability and reducing resilience is dependent on who, what, where, and for whom – all of which are socially constructed and change over time (Cutter, 2018). Developing metrics to assess and compare is more feasible if the units of analysis are narrow, and by their nature resilience and vulnerability are embedded in interdependencies between systems, scales, and historical processes: Oliveira et al. (2020), for instance, ranked a group of neighbouring villages in Portugal with a hierarchical cluster analysis encompassing several proxies assessing exposure, vulnerability and coping capacity.

In vulnerability assessments, it is difficult to identify thresholds or benchmarks. When does vulnerability turn into disaster loss? Is it difficult to define a precise value as a threshold? What is the tipping point at which people with certain characteristics must inevitably leave a place or are harmed? As a result, it is preferable to think of it in terms of possible degree ranges (Fekete, 2019). For these reasons, understanding vulnerability as a relative concept should take place in context, allowing for comparison with other similar units of analysis, such as neighbouring communities exposed to similar hazards.

The absence of critical benchmarks, or thresholds, becomes especially important when assessing vulnerability and considering index values. In this case, an absolute value obtained by an aggregation of proxy values achieves significance mostly in relative terms, in comparison to, the values of indexes

[15] Taking the example of a community, fire prone, in which the number of senior citizens (i.e., above 65 years old) is significatively high. Looking at this variable from a merely quantitative approach would be associated with a negative connotation, implying that an ageing population represents an element of vulnerability (Cutter, Boruff, & Shirley, 2003). However, incorporating qualitative elements that contextualise the implications of the variable at local level could challenge such hypothesis. Senior residents in the community, for instance, may be considered as a resource in terms of adaptive capacity, as they retain knowledge on the territory, past episodes of wildfire and their multi-dimensional impact, that may guide the community both in preventing fire risk, preparing to face the hazardous event, as well as in the recovery phase.

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calculated for the other similar units included in the analysis (for example, neighbouring counties/regions/communities).

For example, if vulnerability indexes are calculated for ten counties, each of them would have different values distant from the mean. The values of the indexes for the various counties will be higher or lower than the mean value, and a score can be derived based on a calculated standard deviation, and based on this score, the level of vulnerability of the respective county can be classified as high or low.

Most studies based on Cutter's widely used methodologies (Cutter, Boruff, & Shirley, 2003; Cutter, Burton, & Emrich, 2010; Guillard-Gonçalves, Cutter, Emrich, & Zêzere, 2015), provide a spatial assessment as well as an empirical ranking.

In summary, a vulnerability score (a numerical value that aggregates all the operations performed by collecting values for indicators, aggregating them, and so on) cannot be high or low in and of itself; it can only be high or low by reference (distance) to a mean value, and thus only by reference to other units of analysis that comprise this mean.

Furthermore, if vulnerability assessment (or evaluation of the resilience frameworks) is considered from the perspective of strategy design and setting, it is preferable to use a participatory approach in which communities themselves are involved in the development of indicators and the identification of proxies for data collection, as well as the definition of their weight and vector. Instead of being a top-down approach with metrics elaborated independently, the assessment becomes bottom-up and thus meaningful for end-users.

In most cases, a participatory-interactive methodology is thus desirable, though it may present the challenge of being less amenable to comparisons between different contexts (e.g., between countries), necessitating the establishment of thresholds and benchmarks for the analysis (i.e., if I cannot assess myself against others, I need to fix my own thresholds).

As seen above, relativity is an important factor in determining proxies and indicators (and so developing indexes) of vulnerability and resilience. Previous research concentrated on relativity primarily within a continuous geographical area in which different units of analysis confront a similar hazard (Cutter, Boruff, & Shirley, 2003; ECOSTRESS Project, 2015). Other studies (e.g., RESILOC, 2022) take a different approach to assessing resilience, by building a platform for communities to learn from one other's proposed solutions to lowering vulnerability and strengthening resilience[16].

[16] This approach could enable the construction of a relativity viewpoint for observing the selected FirEURisk PSs/DAs. Similar approaches that encourage peer-to-peer learning processes may be identified in efforts and projects that propose peer-review exercises on the issues of resilience and disaster risk reduction amongst cities from diverse national contexts. However, given the nature of the activity, such approaches frequently provide a learning horizon confined to the actors involved. For example, one of the pioneers of the peer-to-peer learning frameworks for resilience targeting cities, is the UScore2 project (DG-ECHO, 2016). UScore2 proposes a peer-review methodology as a further elaboration of a pilot initiative (i.e., UScore DG-ECHO funded project) enabling cities to perform self-assessments on Disaster Resilience Scorecards (i.e. a standard tool developed according to the indicators of the Sendai framework and UNSDIR). The peer-review approach also offered an impact

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4.1.2.3 Vulnerability indicators and indexes

Vulnerability has been assessed and measured in a variety of ways, including the use of vulnerability curves and vulnerability matrices. Geographic information systems (GIS) are increasingly being used to map vulnerability and better understand how diverse events (hydrological, meteorological, geophysical, social, political, and economic) affect human populations. Using indicators has been the most widely used strategy for determining vulnerability among all assessment approaches. These indicators contain (explicitly or implicitly) goals for minimising vulnerability (or building resilience) to natural disasters (Fuchs & Thaler, 2018). Such indicators, according to (Birkmann, 2006), can be defined as variables which are *"an operational representation of a characteristic or quality of a system able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of ... a hazard"*. Therefore, an indicator's potential is based on the degree to which it accurately represents the envisioned goal.

An indicator is a quantitative or qualitative variable produced from observed facts that simplifies and communicates the main features composing a complex situation (Freudenberg, 2003). In general, indicators provide the relative location of the phenomenon being monitored and, when compared over time, can show the magnitude of change (a little or a lot) as well as the direction of change (up or down, growing or decreasing) (Cutter, Burton, & Emrich, 2010).

Composite indicators, also known as indexes, have been used in studies to assess and measure vulnerability and resilience. A composite indicator is made up of many proxies or variables. A composite indicator is an aggregation of individual variables (proxies) or "*thematic sets of variables that represent different dimensions of a concept (or a phenomena) that cannot be fully captured and understood by any individual indicator alone*" (Cutter, Burton, & Emrich, 2010; Burton, Rufat, & Tate, 2018). Indexes provide an integrated view which at the same time allows for the evaluation of the relative contribution of specific components, thereby supporting decision-making and strategy drafting processes (Oliveira, et al., 2020).

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evaluation methodology, which allows cities participating in the exercise to track the impact/changes that resulted from the peer-review learning and decisions. Both proposed procedures (peer review and impact evaluation) are based on qualitative/self-assessment approaches, which allow cities under consideration to determine their own benchmarks and thresholds for self-assessment. The approaches are evidence-based (i.e., checklists and/or presenting information/evidence justifying a specific evaluation) and do not imply the use of statistical data in this sense.

However, the full benefits of such an approach appear to be restricted to the number of participants in the exercise (i.e., the methodology requires commitment on all involved parties, joint decisions on objectives and benchmarks, study visits, etc.).

Although the knowledge generated and exchanged throughout the peer-review process may be shared with the broader public, the learning process (due to its high co-design/participatory nature) will be meaningful only to the actors participating.

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Composite indicators are "increasingly recognised as useful tools for policy making and public communication because they convey information that may be utilized as performance measures" (Cutter, Burton, & Emrich, 2010). One of the most well-known studies of vulnerability[17] that used indicators is SoVI®, Cutter et al.'s Social Vulnerability Index (Cutter, Boruff, & Shirley, 2003).

According to Cutter, Burton, & Emrich (2010), the construction of composite indicators, or indexes, proceeds through a series of steps:

- The first step involves the development of a conceptual framework to provide the basis for selecting the variables or the proxies, a model, and a set of dimensions.
- The identification of variables/ proxies that are relevant and representative, which are developed in the extant literature and, most importantly, which are available and reliable in national or regional data sets.
- The third step includes standardization, because the raw data values should be transformed into comparable scales utilizing percentages, per capita, and density functions, to avoid problems of mixing measurement units that are different[18].

The SoVI® is a consolidated instrument for analysing disparities in community capacity to prepare for, respond to, and recover from disasters. The index includes a collection of concepts/indicators culled from earlier conceptualisations and models[19] and aggregated to describe the complex phenomena of a place's social vulnerability and the set of assumptions that surround them.

[17]The Community Vulnerability assessment build on the SoVI® framework, the SoVI® model represents the gold standard of vulnerability studies, and the indicators and variables used across the world in various vulnerability assessment use it as a base for further adaptations. One of the adaptations, upon which FirEUrisk Societal Vulnerability and Resilience assessment builds is ReSVI – Relative Social Vulnerability Index, elaborated within the framework of the ECOSTRESS project by ISIG, and subsequently reframed and adapted for the development of RESILOC project.

[18] Keeping in mind the relative character of vulnerability, the use of indicators thus should be integrated into a comparative approach of indicators across a set of different locations (at different or similar scales). Sometimes it is important to conduct research at smaller scales, which give a picture of a local situation, and many authors highlight this as a difficulty, since most data are collected and aggregated at upper levels, i.e. national or regional, yet they also highlight that "it is important to look at locally-derived factors, rather than relying solely on nationally collected data" (Frazier, Thompson, Dezzani, & Butsick, 2013, p. 96).

[19] The Hazards-of-Place approach highlights the need to prioritize two important questions, i.e. 'the vulnerability of what, and the vulnerability of whom', in other words vulnerability has to be understood in reference to particular places and times. The Hazards of Place model has typically been implemented in a Geographic Information System (GIS), to map and compare the vulnerability of different geographical locations (places) by spatially integrating biophysical and social vulnerability (Burton, Rufat, & Tate, 2018). In this model, the interaction of social, political, and economic factors—interacting with one another on the one hand, and with the physical environment on the other hand—creates a mixture of risks and hazards that affect people and the places they populate (riskscapes or hazardscapes) (Cutter, Mitchell, & Scott, 2000). Here, social vulnerability is

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This model was further developed, and SoVI® 2010-14 represents a departure from previous versions in the construction of the SoVI® measure. New developments in vulnerability science theory and practise emphasise the limits of family structure, language difficulties, vehicle availability, medical disability, and healthcare access in disaster planning and response, necessitating the inclusion of such aspects in SoVI® (Cutter & Emrich, 2017).

4.1.3 Societal Vulnerability to Wildfires

As already outlined in the previous paragraphs, societal vulnerability indicates the propensity for human well-being to be damaged by disruption to individual (mental and physical health) and collective (health, education services, etc.) social systems and their characteristics (e.g., gender, marginalisation of social groups) (Birkmann, et al., 2013). Social systems may be framed as "social space" as well; its boundaries are defined by the "political, economic, and institutional capabilities of people at a specific time and place" (Burton, Rufat, & Tate, 2018, p. 53).

Societal vulnerability to wildfires refers both to the magnitude of societal impact deriving from wildfires, and the inability of local society to cope with stressors to which it is exposed as a consequence of a wildfire. It has, at the same time, a structural and a processual dimension. Of course, societal vulnerability may be investigated at a global scale as well, for instance within the broader issue of climate change. Yet for the purpose of the proposed methodological framework of this chapter, the analysis will be framed at a local scale.

The following insights on societal vulnerability to wildfires are organised starting from two conceptual cores which are interrelated,

- Sensitivity: the stresses which affect exposed elements, i.e., the correlation between stresses and elements characterising the local society.
- Adaptive capacity/coping mechanisms: the presence or lack of skills, resources, opportunities which allow to cope with stresses investing exposed elements.

4.1.3.1 On sensitivity variables

Even though wildfire can be simply described as a consequence of the interaction among air mass, topography and fuel dynamics (Contryman, 1972), according to the *FAO Strategy on Forest Fire Management*, 90% of wildfires are caused by human activities and behaviours. In determining a wildfire, human activities and behaviours are clearly interrelated with meteorological conditions, as well as territorial topography and fuel availability. In Mediterranean France, for instance, strong winds, together with high temperatures, are considered the main drivers of the largest fires and entrapments (Lahaye, et al., 2018).

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understood to be influenced by a series of broad features: lack of access to resources, including information and knowledge, limited access to political power and representation, certain beliefs and customs, weak buildings or weak individuals, infrastructure and lifelines. Based on previous research, this study posits that amplifying or reducing overall vulnerability to hazards is dependent upon certain demographic and housing characteristics, specifically: age, race/ethnicity, income levels, gender, building quality, public infra-structure (Cutter, Mitchell, & Scott, 2000, p. 726).

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The relationship among the above mentioned factors is, however, far from being linear and simple. Martínez et al. (2009) introduce their research by stating that, still nowadays, many aspects of wildfire analysis remain obscure, undermining the possibilities for an effective strategy preventing them. Leone et al. (2009), for instance, underline that in the Mediterranean area human-related causes of fire are no longer mainly linked with traditional systems of life, as the intervened changes in land use, mainly with the abandonment of agricultural land, decrease and aging of rural population and neglection of forests resulting in poor managing and exploiting strategies, contribute to the increasing quantity of biomass exposed to fire risk.

As a preliminary step of their research, Martínez et al. (2009) isolated seven groups of anthropogenic risk factors associated with wildfires:

- **Socio-economic transformations** in rural areas: rural exodus, abandonment of traditional activities in agricultural and forest lands, rural population aging or declining, fuel accumulation in abandoned agricultural lands, lack of interest in conservation and forest management by the remaining rural population.
- **Human presence** and socio-economic transformations in urban areas: increase in recreational use of the forest, tourist pressure on forest areas, and demand of forest areas for urban growth.
- Persistence or transformation of **traditional activities** linked to fire in rural areas: burning for improvement, regrowth or maintenance of pastures; agricultural burning to eliminate stubble, weeds, field margins, pruning remains, etc.; fires for soil fertilization, shrub land clearing, etc.
- **Accidental or negligent events** related to electric lines, hunting reserves, road transit, railways, military exercises.
- **Landscape structure and housing patterns**: fragmentation, patch connectivity, housing configuration.
- **Indirect factors of intentional fires**, i.e., declaration of protected areas, land use regulations, property conflicts, ‘‘fire industry’’ to obtain jobs or subsides in extinction and site-restoration work, etc.
- **(Lack of) forest policy**: insufficient protection and management of forest land; dissuasive factors associated to fire suppression resources in place (watch-out towers, presence of fire crews).

In their subsequent research aimed at developing a predictive model of fire risk, the authors identified 12 relevant variables positively associated with higher fire occurrence in 6066 Spanish Municipalities:

- Density of agricultural machinery.
- Density of agricultural plots.
- Persistence of livestock under traditional management.
- Unemployment rate.

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- Rural population decrease between 1950 and 1991.
- Urban–forest interface density, density of roads.
- Density of railways.
- Urban population increase between 1950 and 1991.
- Density of the interface between risk infrastructures (waste dumps, mines, quarries, areas under construction, roads more than 100 m wide) and forest areas.
- Percentage of municipal land in protected natural areas.
- Agricultural area which became forest land in 1970–1990.

Another variable, the increment in the number of owners of agrarian holdings in 1989–1999, was inversely associated with fire risk, meaning that more intensive and centralised agriculture patterns diminished fire risk.

A similar research conducted by analysing data from Sardinia (Italy) and Corsica (France) confirmed that fires on those islands are mainly determined by human activities (e.g., negligence in the maintenance of the territory, agro-pastoral land use, arson) and that «roads and other anthropogenic features are of strong interest for wildfire mitigation» (Ager, Preisler, Arca, Spano, & Salis, 2014).

Vallejo-Villalta et al. (2019) describe the evolving dynamics of wildfires in Southern Spain as the result of a «symbiosis between some natural conditions (terrain, climate and state and type of vegetation) that favour the outbreak and spread of fire and the depth transformations experienced by societies and the rural and/or natural environment in recent decades» (p. 1). The components of these changes are outlined as follows:

- Mass abandonment of traditional activities (i.e., farming, livestock-raising and forest utilisation).
- Increase of uncontrolled property speculation.
- Changes in land uses, for instance towards rural tourism and second homes.
- Disputes.
- Hunting interests.
- Creation of pastures.
- Rural depopulation.

According to this study, 96% of fires in Spain and 80% of fires in Andalusia were caused, directly or indirectly, by human activities.

The review study produced by Costafreda-Aumedes et al. (2017) resumed a list of the most influential variables increasing or lowering fire risk, both on short-term and long-term. Variables are classified according to five categories (weather and danger; physiography; vegetation/fuel; human-related; and other).

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Human-related variables in the short-term are:

- Distance to roads (inversely related with fire risk).
- Road density (directly related with fire risk).
- Distance to settlements (inversely related).
- Urban areas (inversely related).
- Distance to railroads (inversely related).

Human-related variables in the long-term are:

- Distance to roads (inversely related).
- Road density (directly related with fire risk).
- Distance to settlements (inversely related).
- Population density (directly related).
- Building density (directly related).
- Distance to railroads (inversely related).
- Railroad density (directly related).
- Distance to recreational areas (inversely related).
- Protected areas (directly related).
- Per capita GDP (directly related).

4.1.3.2 On Adaptive Capacity variables: land management policies and practices

In the broader framework of human activities, consolidated and/or emerging patterns of territorial development, as well as explicit local policies, play a relevant role in increasing or decreasing both exposure and sensitivity to the risk of wildfire. It is not always easy to evaluate policies and practices in terms of their ultimate effects according to these outcomes; Moritz et al. (2014), for instance, state that «the 'command and control' approach typically used in fire management neglects the fundamental role that fire regimes have in sustaining biodiversity and key ecosystem services» (p. 58). In a way, thus, fire management procedures, which are often aimed at combating wildfires when they appear rather than preventing and managing the risk of wildfires itself, may be proven ineffective on the long run. The authors indeed promote an approach based on the 'coexistence' with wildfires. By observing the current situation in the Mediterranean Basin, Fernandes (2013) too stresses the position that predominant fire management practices are more focused on fire suppression rather than land management issues; this particularly matters when addressing wildfires issue in wildland-urban interfaces (WUI), as the high risk of ignition in such areas poses great threats on human lives and properties.

Jucker Riva et al. (2018) investigated the impact of land management practices (LMPs) in the enhancement of forests and rangelands resilience *vis-à-vis* environmental disturbances such as pests

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and diseases, droughts, floods, and fires. The research was conducted by observing eight sites in five countries in Southern Europe. The research isolated 16 LMPs, clustered in five groups:

- **Clearing of vegetation** (i.e., post-fire conservation logging, post-fire traditional logging, selective forest clearing, cleared strip network system/firebreaks, clearing of fire-prone seedier species). Clearing of vegetation reduces the available biomass in fire-prone areas; it may be combined with economic activities such as the wood extraction for productive purposes. This bundle of practices is proved to be positive against fires.
- **Managed grazing** (i.e., Metallic fences to regulate grazing, controlled grazing in spring months). Grazing management practices are aimed at regulating/limiting the access of animals to certain areas during some periods of the year; they are proved to be positive, but not resistant in relation to fires.
- **Planting of shrubs** (i.e., Plantation of semiarid woody species with micro-catchments, spatially diverse plantation of diverse semiarid woody species, plantation of semiarid woody species on terraces, planting of resprouted shrubs and trees). Planting of shrubs practices restore degraded areas by increasing the vegetation cover triggering the natural evolution of ecosystems; they are proved to be effective against fires.
- **Planting of trees** (i.e., Afforestation with *Pinus halepensis* after fire, grazing land afforestation with carob trees, planting carob and olive trees to prevent erosion). Planting of trees works as a restoration practice, but differently from the planting of shrubs it is scarcely resistant against fire.
- **Other practices** (i.e., Carob tree protection from rats, fodder provision to animals during summer).

4.1.3.3 The Forest Fire Circle: a theoretical framework of exposure-sensitivity-coping mechanisms relation

In the previous paragraph several typologies of fire ignition factors directly or indirectly linked with human presence and its relationship with the environment were presented. By theorising the Forest Fire Circle, Tàbara, Saurí and Cerdan (2003) propose that, rather than simply co-existing, most of the abovementioned factors – more particularly socioeconomic and demographic trends, the crisis of the traditional agriculture and global climatic trends – are deeply interrelated, generating a vicious circle which leads to the increasing of probability and frequency of occurrence of fires in Mediterranean forest ecosystems. The figure clearly represents the tight intertwining among the different meanings of vulnerability – exposure, sensitivity, (lack) of adaptive capacity – as well.

The model describes four main drivers of wildfires risk in the Mediterranean area:

- Impoverished environmental and socioeconomic conditions with an increasing rural abandonment.
- Warmer and drier bioclimatic conditions.
- Growing presence of communication and power infrastructures in forested areas.

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- Weakened forest culture, loss of traditional forest uses, and local knowledge associated with environmental management.

The combination of the abovementioned factors leads to:

- Shift from low productivity crops to forests.
- Increased biomass of undergrowth fuels.
- Increased forest continuity.
- Reduced local control capacity.

As the first ones may be intended as global factors related with long-run trends in the transformation of the socioenvironmental context, the second ones are those factors directly observable when focusing on the short-run. The model, thus, also suggests that effective strategies to deal with wildfires risk need to consider short-term actions to anticipate and prevent the analysed situations during the dry season, and medium/long-term actions to contain the potential growth of impacts before the next dry season arrives.

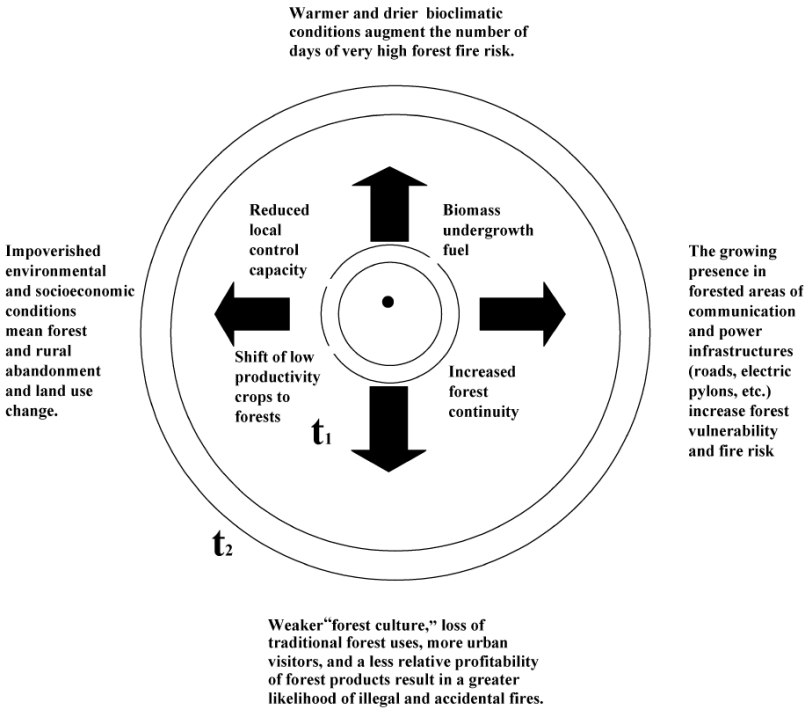


Figure 5: The Forest Fire Circle (Tàbara, Saurí, & Cerdan, 2003)

4.2Methodology for Societal Vulnerability and Resilience Assessment in FirEUrisk: the use of relative indices - RESVIs

The aim of the proposed methodological framework (ReSVI) is mainly that of supporting local communities in analysing their vulnerability to hazards as a starting point for designing and implementing strategies that aim to strengthen adaptive capacities and overall resilience at the local level.

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This section proposes a methodology to assess societal vulnerability and resilience in relation to wildfires at a community level (focusing on a territorial, administrative, or statistical unit). The developed methodology, called ReSVI - Relative Societal Vulnerability Index, focuses on the analysis of the capitals interacting and constructing a local community (i.e., the unit of analysis of the framework). These capitals are represented by ReSVI through the following dimensions:

- **Social dimension** – describing the community in terms of demography, identity, vitality (e.g. socio-demographic characteristics, local activism, access to information, etc).
- **Economic dimension** – describing the overall resources and assets within a community that ensure the communities' wellbeing (e.g., average income, distribution of resources, occupational related aspects, etc.).
- **Institutional dimension** – describing the institutional and political resources in communities, as well as participation frameworks fostering citizens' engagement in decision-making processes.
- **Human capital dimension** – describing the knowledge, skills, and capacities within communities, as well as the potentiality to deploy those skills and capacities (e.g., health related variables).

Environmental dimension (i.e., the context) – describing the tangible assets that shape the community, understood both as natural and infrastructural/built. The methodology considers both static and dynamic variables, that pertain to 5 dimensions of societal vulnerability at community level, identified as relevant for promoting a more holistic approach on such frameworks. Such dimensions are assessed both in quantitative terms (i.e., based on statistic data) and in qualitative terms, through the engagement of local stakeholders that support the assessment of relevance of proposed indicators and proxies, based on their knowledge of the context at hand (i.e., for the case of FirEURisk, such context knowledge and awareness was provided by the Pilot Sites coordinators).

The proposed indexes (ReSVI – Relative Social Vulnerability Index) are built in relative terms (i.e., comparative terms), implying that each unit of analysis (i.e., communities within Pilot Sites) is assessed against an area of reference (i.e., neighbouring territorial/administrative units).

Within the framework proposed by this chapter, vulnerability and resilience are considered from a systemic view, such as the approach proposed by the Conceptual Framework on resilience of the European Commission[20]. This systemic approach implies that resilience is highly dependent on the context, thus requiring to be analysed within its multidimensional system of references (i.e., ecological, social, economic, political) (Manca et al, 2017). Stemming from previous research

[20] Illustrated within the Report Building a Scientific Narrative Towards a More Resilient EU Society, JRC Science for policy report, 2017

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experiences in the field of social vulnerability[21], and drawing from the main research frameworks of vulnerability studies, this methodological framework proposes a community perspective, which analyses vulnerability and explores resilience-related considerations within a multidimensional system, such as 'the community'. This framework ultimately allows for the integration of local knowledge, practices, and functional social relations into the assessment of the vulnerability of a local community contributing to a deeper understanding of key factors, which - otherwise - would be possibly over or under-estimated in a larger scale analytical framework.

The following table aims to summaries the main steps performed for the implementation of the proposed methodological framework for assessment of societal vulnerability to wildfires at community level:

[21] Relative Social Vulnerability Index and SWOT Analysis of Coastal Case Studies in the Upper Adriatic performed by ISIG within the Project ECOSTRESS (Ecological COastal Strategies and Tools for Resilient European SocietieS) (2013-2015); project co-financed by the European Union ECHO/SUB/2013/671461. RESILOC H2020 Project (2019-2022)

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Table 5: Summary of objectives and steps of Societal Vulnerability at community level

OBJECTIVES	STEPS	OUTPUTS
Elaborating an assessment tool for societal vulnerability to wildfires at community level.	1. Literature Review	• Conceptual framework for Societal vulnerability to wildfires (i.e., update of previous work on multi-hazard perspective with a focus on fire risk/wildfires)
I. Highlighting major areas of vulnerability at (local) community level	1. Definition of Indicators and Proxies – based on literature review	• FirEUrisk Preliminary list of Indicators and proxies (Annex A1)
II. Supporting relevant actors (e.g., Local Authorities, decision-makers, relevant practitioners) in vulnerability-reducing and resilience-enhancing strategies	2. Participatory review of Indicators and Proxies – with Pilot Site coordinators (i.e., relevant stakeholders)	• Assessment of relevance of vulnerability indicators and proxies (Annex A1)
III. Supporting strategic planning	3. Data collection	• Consolidated list of FirEUrisk Indicators and Proxies for each Pilot Site (Annex A1)
	4. Analysis	• Preliminary ReSVI results for 3 out of 5 Pilot Sites

4.2.1 Building FirEUrisk RESVIs Preliminary List of Vulnerability Indicators and Proxies

In terms of operational steps, the research framework implied literature review, quantitative data collection and data analysis (i.e., survey, secondary data, official databases, etc), qualitative data collection by means of focus groups, interviews.

The elaboration of the preliminary list of dimensions, indicators, and proxies to assess social vulnerability and resilience was based on thus, both literature review and previous research efforts in the field of vulnerability assessment for flood-prone communities (i.e., ECOSTRESS – the RESVI Index) and in a multi-hazard perspective (i.e., RESILOC – the RESILOC Vulnerability Inventory). This inventory has been previously validated, in the framework of the abovementioned projects, to be significant for a wide range of environmental disaster risks. Such previous knowledge has been then integrated with fire-specific analysed sources, the contribution of which has, for the most part, already been presented in this dissertation. Such integration was carried out with the aim of finetuning the consolidated inventory in order to better grasp the specific characteristics of wildfire risk.

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Dimensions, indicators, and proxies are here defined as follows:

- Dimensions: the underlying capitals interacting and constructing a community (i.e., the latter being the focus of this analysis).
- Indicators: variables that provide an operational representation of a characteristic of a community (i.e., indicators are grouped per relevant dimensions).
- Proxies: indirect data sources contributing to the assessment of an indicator (i.e., proxies are grouped per relevant indicators).

Starting from the analysis of the original sources, dimensions, indicators, and proxies have been subsequently formally adapted, for instance by:

- Conforming them to EU standards, e.g., by substituting square miles with square kilometres.
- Removing specific chronological references, e.g., editing "Decrease in agricultural area between 1989 and 1999" in "Decrease in agricultural area (time span)".

Stemming from this process, a total of **5 dimensions, 35 indicators and 236 proxies** for the assessment of social vulnerability to wildfires were identified, as highlighted in the tables presented in Annex A1[22].

Used sources were: (Burton C. , 2012) (Eidsvig, McLean, Vangelsten, & Kalsnes, 2011) (ENSURE, 2009) (Baum, Horton, & Choy, 2008) (Tapsell, Tunstall, Green, & Fernandez, 2005) (Oliveira, et al., 2020) (Cardona, 2005) (ECLAC, 2011) (Leone, Koutsias, Martínez, Vega-García, & Allgöwer, 2003) (Jucker Riva, et al., 2018) (Costafreda-Aumedes, Comas, & Vega-Garcia, 2017) (Martínez, Vega-Garcia, & Chuvieco, 2009) (Parsons, et al., 2020).

4.2.2 Operationalisation of Societal Vulnerability Index

The following paragraphs illustrate the steps to be taken into consideration to operationalise the Societal Vulnerability Index for the purpose of the analysis of (societal) vulnerability in FirEURisk Pilot Sites.

4.2.2.1 Decision about units of analysis

First of all, a decision must be made about the selection of the most appropriate units of analysis, which need to be at least three in order to be able to set up the relative Index. Units of analysis, which must be consistent with the methodology set for the collection of proxies, can be categorised according to the relationship with the observed/analysed community; in this sense, they can have:

- A "vertical" relationship, meaning that the selected units of analysis correspond to administrative tiers which are higher than the observed community. For instance, if the analysed territory is a Municipality, units of analysis with a "vertical" relationship with the Municipality are the Province, the Region, or the State.

[22] The table represents the result of the literature review activity and illustrates the preliminary selection of proxies and indicators (grouped per relevant dimension) that will be proposed to the involved FirEURisk pilot sites. For each presented proxy the sources are illustrated (i.e., author or authors that have used the proxy in relation to vulnerability analysis research).

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- A “horizontal” relationship, meaning that the selected units of analysis correspond to administrative units which stand at the same level of the observed community. For instance, if the analysed territory is a Province, units of analysis with a “horizontal” relationship with the Province are other Provinces, e.g. those bordering with the observed one.
- A “mixed” relationship, meaning that the selected units of analysis have “vertical” and “horizontal” relationships with the observed community. For instance, if the analysed territory is a Municipality, mixed units of analysis are two contiguous Municipalities and the Region including all the three Municipalities.

4.2.2.2 Selection of Indicators and Proxies

The preliminary list of Vulnerability indicators and proxies per each dimension has been identified by means of the literature review. This list has been reviewed within the Workgroup of WP1 (Scientific Coordinator, WP leader, Task leader).

Subsequently, in order to be operationalised the list needs to be reviewed by local actors/stakeholders (in the case of FirEUrisk, Pilot Site Coordinators) in order to filter it through the ‘lenses’ of local knowledge related with the specific context of analysis. The assessment is conducted at the Indicator and Proxy level using the following criteria:

- Relevance of proposed Indicators and Proxies, in relation with the context.
    - First, relevance is intended as the degree through which a Proxy/Indicator is assessed to represent a phenomenon which has consequences on the societal arrangement at the level of analysis. A 0 is attributed to Proxies and Indicators with no relevance in the context of analysis; Proxies and Indicators with medium relevance are labelled with 0.5, while Proxies and Indicators with high relevance are labelled with 1.
    - Relevance can also be interpreted in terms of aspects which give a contribution in increasing societal vulnerability (thus with a positive orientation, +1, applied to the Z-score during the calculation of the Index) and aspects which give a contribution in lowering societal vulnerability (thus with a negative orientation, -1, applied to the Z-score during the calculation of the Index).
- A second assessment is conducted on the availability of data which are relevant, both in positive and negative terms, for the societal vulnerability assessment. Availability of data is checked by PS Coordinators by consulting statistical databases, but also taking into consideration the possibility to assess specific societal aspects through qualitative means, e.g., through focus groups involving relevant community stakeholders.

Interaction and data gathering is facilitated by means of an Excel tool.

4.2.3 Data collection and elaboration

As the Selection of Indicators and Proxies is completed, the Excel tool is filled in with the relevant statistical data, by consulting local, national and international databases, and/or through the collection of qualitative data through the means of focus groups, surveys and other data collection tools.

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This paragraph illustrates the steps that must be taken in order to calculate the Societal Vulnerability Index:

- Proxies deemed as relevant and presenting at least two data available are taken into consideration.
- The Z-score computation is applied to the selected proxies, according to the formula:

Equation 2: Z-Score Computation

$$Z = \frac{\mathrm{X} - \mu}{\sigma}$$

Where X is the proxy value, μ is the mean value of all proxy values, and σ is the standard deviation of all proxy values.

- Z-score results are then multiplied by +1 or -1 according to the influence which the proxy exercise on the increase (+1) or decrease (-1) of societal vulnerability, respectively.
- The obtained values are then converted on a 0 to 1 scale, where 0 is the smallest magnitude and 1 is the largest magnitude the Z-score could reach. In order to do so, two methodologies can be followed, the first one being more indicated for small sets of units of analysis, the second one for larger sets.
    - In the first case the approach suggested by Shiffler (1988) is taken into account, by calculating the largest potential magnitude of the Z-score:

Equation 3: Z-Score Potential Magnitude Computation

$$\frac{n-1}{\sqrt{n}}$$

Where n is the data set size.

The Z-score is thus transformed in an index on a 0 to 1 scale, using the formula:

Equation 4: 0-1 Scale Z-Score Normalisation (first version)

$$\frac{(x + M_z)(M_t - m_t)}{2M_z + m_t}$$

Where x is the Z-score value, m is minimum, M is maximum, z is the Z-score potential magnitude and t is the theoretical data. As in this case, M_t equals 1, while m_t equals 0, the formula can be simplified as follows:

Equation 5: 0-1 Scale Z-Score Normalisation (first version, simplified)

$$\frac{(x + M_z)}{2M_z}$$

    - In the second case, real maximum and minimum Z-score values expressed within the pool of units of analysis are taken into account, by applying the 0-1 scale Z-Score normalisation formula as follows:

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Equation 6: 0-1 Scale Z-Score Normalisation (second version)

$$\frac{(x - m_x)}{M_x - m_x}$$

Where x is the Z-score value, m_x is the lowest Z-score value within the pool of data, and M_x is the highest one.

- The normalised Z-score is then multiplied for 0, 0.5, or 1, according to the relevance assessed in relation to the analysed context (where 0 is no relevance, 0.5 is medium relevance, and 1 is high relevance).
- The value obtained following the above-mentioned methodology refers to a single proxy. To obtain a significant index, it is necessary to make a simple mean of all proxies pertaining to the same indicators. For example, if information is available on proxies like "Percentage of single parent families" and "Percentage of households with children", the simple mean of both proxies represents the Societal Vulnerability Index in terms of Family Structure.
- Eventually, another simple mean among all Societal Vulnerability Indexes pertaining to the same Dimension (e.g., the Social Dimension) produces the Societal Vulnerability Index for that Dimension.

4.3 Results of Societal vulnerability and resilience assessment in FirEURisk

4.3.1 Overview Across the FirEURisk Pilot Sites Pilot Sites

To showcase the implementation of the Societal Vulnerability Index, the above-mentioned operative steps have been proposed to all FirEURisk Pilot Site Coordinators.

Table 6 shows the state of the art regarding the progress of the demonstrative implementation of the Index in every Pilot Site:

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Table 6: State of the art of Societal Vulnerability Index implementation in FirEURisk Pilot Sites

	Preliminary meeting led by ISIG	Definition of units of analysis	Shortlisted DIP - relevance	Shortlisted DIP - availability	Data collection	Data elaboration	Analysis and discussion of results
PS1 – North Europe (RISE)	19/8/22						
PS2 – Central - Eastern Europe (TUD)	9/8/22		31/8/22				
PS3 – Mediterranean Portugal (ADAI)	9/8/22	16/9/22	9/9/22	9/9/22	22/12/22	Jan 2023	Jan 2023
PS4 – Mediterranean Spain (UdL)	19/7/22	19/7/22	25/8/22	25/8/22	24/12/22	Jan 2023	Jan 2023
PS5 – Mediterranean Greece (AUTH)	13/7/22	8/11/22	31/1/23	31/1/23	31/1/23	Feb 2023	Feb 2023

4.3.2 Demonstrative Application of the Societal Vulnerability Index

4.3.2.1 PS3: Mediterranean Portugal

As presented in Table 6, PS3 – Mediterranean Portugal, led by ADAI, is the Pilot Site where the implementation of the Societal Vulnerability Index has been almost completed, lacking only of the participatory review of the results. For this reason, the present chapter illustrates how the Index has been implemented in that Pilot Site.

4.3.2.1.1 Units of analysis

PS3 – Mediterranean Portugal covers the territory of 17 Municipalities in Portugal, belonging to two different NUTS-3 levels, i.e., the Coimbra Region (Comunidade Intermunicipal da Região de Coimbra) and the Leiria Region (Comunidade Intermunicipal da Região de Leiria).

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Within the framework of the participatory research, the Pilot Site coordinator (ADAI) selected the following administrative units as the ones to be investigated through the implementation of the Societal Vulnerability Index:

- Municipality of Lousã (Coimbra)
- Municipality of Figueiró dos Vinhos (Leiria)
- Municipality of Castanheira de Pêra (Leiria)
- Comunidade Intermunicipal da Região de Coimbra
- Comunidade Intermunicipal da Região de Leiria

However, in order to make the analysis more accurate by increasing the number of analysed units, the following Municipalities have been also taken into consideration:

- Municipality of Arganil
- Municipality of Mortágua
- Municipality of Oliveira do Hospital
- Municipality of Penela
- Municipality of Alvaiázere
- Municipality of Ansião
- Municipality of Pedrogão Grande

Furthermore, the following levels have been also taken into consideration when the corresponding data was available:

- Centro Region (NUTS-2 level)
- Continente (NUTS-1 level)
- National level

This brings the total maximum number of units of analysis to 15.

4.3.2.1.2 Selection of Indicators and Proxies

ADAI then proceeded by selecting those Indicators and Proxies, among the ones listed by means of the literature review, which were deemed as relevant for the context of the Mediterranean Portugal Pilot Site. During this phase, the contribution of local actors is crucial, as they are endowed with the local knowledge needed to perform an effective selection.

Indicators and Proxies have been assessed both in terms of relevance (none, medium, high relevance) and orientation (differentiating between aspects which give a contribution in increasing societal vulnerability, and aspects which help lowering it).

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Then, ADAI assessed Indicators and Proxies in terms of data availability, crossing the proposed list with datasets available from different sources of information. During this phase, a few additional Proxies were proposed as alternative 'sources of information' to substitute or integrate the initial selection.

The result of this process is shown in Annex A1.

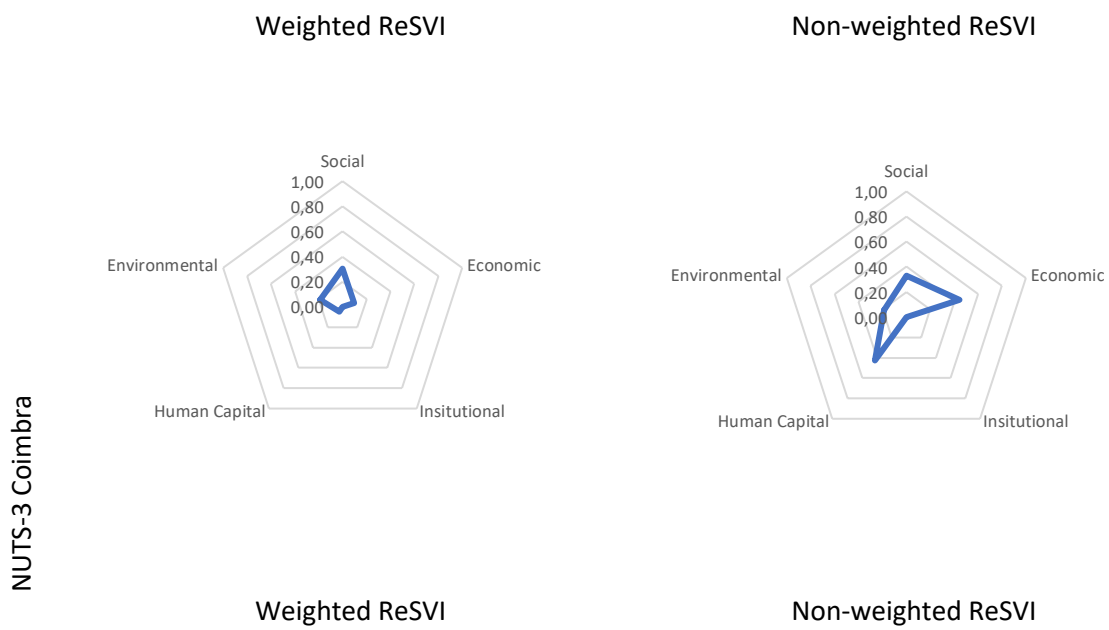
4.3.2.1.3 Index calculation

After ADAI provided all the gathered information, ISIG proceeded to calculate the Index. To better showcase the functionality of the Societal Vulnerability Index, the calculation has been made in two versions:

- The first one considering the relevance assessment for each Proxy.
- The second one considering all the Proxies with available data as equally (highly) relevant.

The full results are shown in Tables within Annex A1.

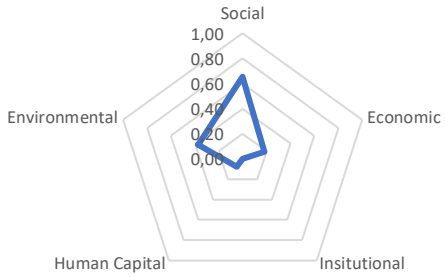
The following figures show the performances obtained by the five units of analysis according to the five Dimensions the Index is composed by[23].



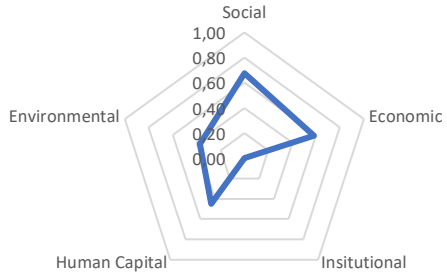
[23] As reported in the Annex, data for the Environmental Dimension was not collected.

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NUTS-3 Leiria

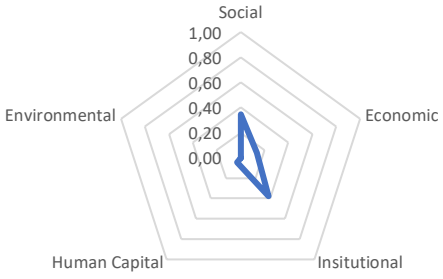


Weighted ReSVI

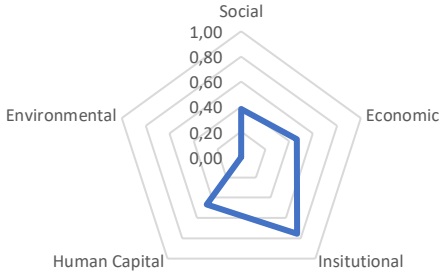


Non-weighted ReSVI

Municipality Lousã

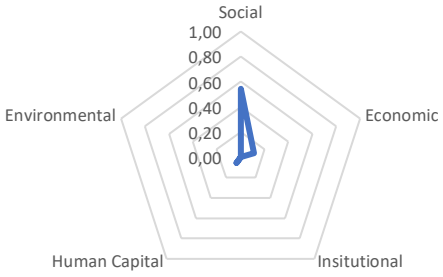


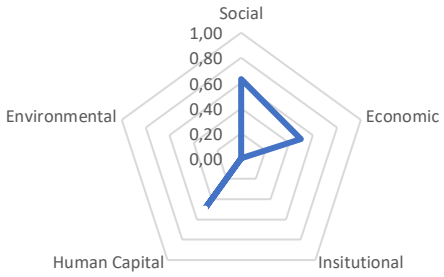
Weighted ReSVI



Non-weighted ReSVI

Municipality Castanheira de Pêra





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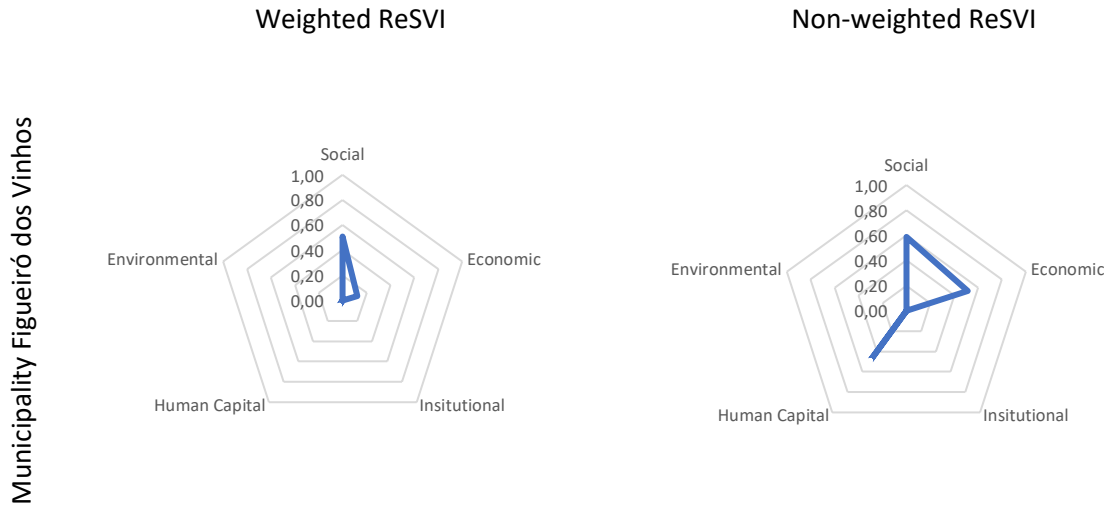


Figure 6: Weighted and non-weighted ReSVI values for the selected units of analysis, PS3

4.3.2.1.3.1 Social Dimension

From a social perspective, the NUTS-3 Coimbra region is the least vulnerable (0.34) while the NUTS-3 Leiria region is the most vulnerable (0.69). Among the inquired Municipalities, Castanheira de Pêra is the most vulnerable (0.61), while Lousã is the least vulnerable (0.41).

According to the Age indicator, the most vulnerable unit of analysis is Castanheira de Pêra (0.61), while the least is Lousã (0.41). The Migrations, Race and Ethnicity indicator is surveyed only at a NUTS-3 level according to this perspective, Coimbra Region stands as less vulnerable (0.22) if compared to Leiria (0.94).

Non-weighted ReSVI index produces the same results, as all available proxies were deemed as highly relevant (1).

4.3.2.1.3.2 Economic Dimension

In the Economic Dimension, the NUTS-3 Coimbra region is again the least vulnerable level of analysis (0.47) while the NUTS-3 Leiria region is the most vulnerable one (0.56). All the three Municipalities stand on similar levels, ranging from Castanheira de Pêra (0.49) to Figueiró dos Vinhos (0.50) to Lousã (0.51).

By analysing the single indicators, it is possible to state that the results according to Wealth and Socio-economic are all very similar, between 0.51 and 0.52. The analysis on Primary Sector shows less vulnerability in the Coimbra Region (0.40) than in Leiria (0.66).

Non-weighted ReSVI brings into play information regarding the Business structure, where the most vulnerable units of analysis are the two Municipalities of Figueiró dos Vinhos (0.65) and Castanheira de Pêra (0.64), while the Leiria Region is the least vulnerable (0.29). The good performance of the Leiria Region in terms of Business Structure contributes to a lower non-weighted vulnerability index in the Economic dimension (0.58) if compared against the weighted index.

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4.3.2.1.3.3 Institutional Dimension

For what concerns the Institutional Dimension, the only surveyed unit of analysis (Municipality of Lousã) has a score of 0.76.

4.3.2.1.3.4 Human Capital Dimension

By analysing the weighted index, in the Human Capital dimension the only indicator deemed with relevance and showing available data is the one regarding Occupation, where the Coimbra Region has the best performance (0.41) while the Municipality of Castanheira de Pêra is the most vulnerable one (0.53).

The non-weighted index allows for an analysis of Health Services too, where, however, all the units of analysis totalise a similar score, ranging from 0.42 (Lousã, Castanheira de Pêra) to 0.46 (Coimbra).

4.3.2.1.3.5 Environmental Dimension

The Environmental Dimension is composed by data which were not collected at a Municipality level; this is why it is possible to investigate only the two units of analysis of Coimbra region and Leiria region. The firs one totalises the best result (0.19) even though the Leiria region (0.37) shows a lower vulnerability in terms of physiography (0.16). Non-weighted index brings to the same results as all available proxies were deemed as highly relevant (1).

4.3.2.2 PS4: Mediterranean Spain

4.3.2.2.1 Units of analysis

PS4 – Mediterranean Spain covers the whole territory of the Province of Barcelona, which is composed of 314 Municipalities. Within the framework of the participatory research, the Pilot Site coordinator (UdL) decided for considering all the Municipalities as the units of analyses where to apply the Societal Vulnerability Index.

4.3.2.2.2 Selection of Indicators and Proxies

UdL then proceeded by selecting those Indicators and Proxies, among the ones listed by means of the literature review, which were deemed as relevant for the context of the Mediterranean Spain Pilot Site. In order to perform this activity, UdL firstly asked ISIG to perform a first shortlisting, which has been made by looking at those references which were directly related with wildfire studies.

Indicators and Proxies have been then assessed both in terms of relevance (none, medium, high relevance) and orientation (differentiating between aspects which give a contribution in increasing societal vulnerability, and aspects which help lowering it).

Then, UdL assessed Indicators and Proxies in terms of data availability, crossing the proposed list with datasets available from different sources of information.

The result of this process is shown in Annex A1.

4.3.2.2.3 Index calculation

After UdL provided all the gathered information, ISIG proceeded to calculate the Index. In order to better showcase the functionality of the Societal Vulnerability Index, the calculation has been made in two versions:

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- The first one considering the relevance assessment for each Proxy.
- The second one considering all the Proxies with available data as equally (highly) relevant.

Results obtained by the application of ReSVI in the 314 Municipalities composing the Mediterranean Spain Pilot Site (PS4) are shown in the overview table (Annex A1). A more detailed analysis of the results, focussing on one or a group of the above-mentioned Municipalities, can be provided on request, also in the future stages of FirEURisk project.

4.3.2.3 PS5: Mediterranean Greece

4.3.2.3.1 Units of analysis

PS4 – Mediterranean Greece boundaries have been the object of a review during the project implementation: the PS area corresponds to the Regional Unit of Eastern Attica (NUTS-3 Region).

Within the framework of the participatory research, the Pilot Site coordinator (AUTH) suggested initially to take in consideration Eastern Attica Region and Rafina-Pikermi Municipality as the two units of analysis to be investigated. After assessing an important lack of data for the Municipality level, the analysis then focussed only on the Eastern Attica Region, compared with other same-level and superior units of analysis, namely:

- Attica Region (NUTS-2)
- Regional Units of the Section of Athens (merging four NUTS-3 levels)
- Regional Unit of the Northern Section of Athens (NUTS-3)
- Regional Unit of Western Attica (NUTS-3)

4.3.2.3.2 Selection of Indicators and Proxies

The relevance assessment of Indicators and Proxies has been indirectly performed through the data collection activity: all collected data have been considered as reporting relevant information for the Greek PS.

4.3.2.3.3 Index calculation

After AUTH provided all the gathered information, ISIG proceeded to calculate the Index; in this case, weighted and non-weighted version produced the same results, as all collected Proxies were deemed as equally relevant (1).

The full results are shown in Tables within Annex A1.

The following figure shows the results obtained for Eastern Attica NUTS-3 Region.

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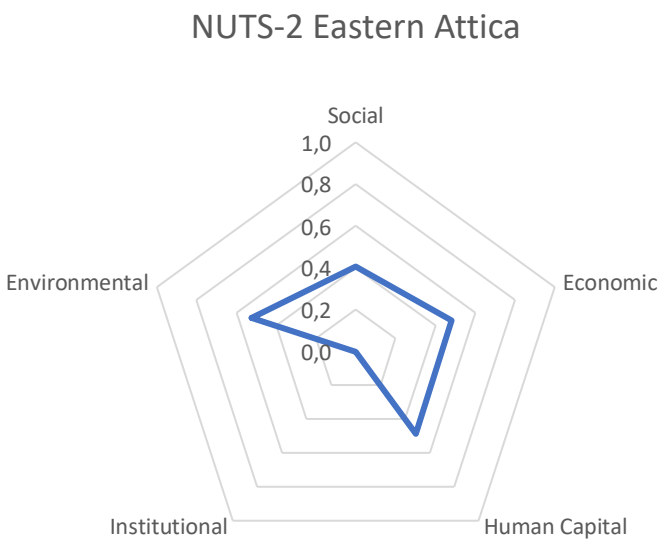


Figure 7: ReSVI values for the selected unit of analysis, PS5

4.3.2.3.3.1 Social Dimension

The NUTS-2 Eastern Attica Region shows a good performance in the Social Dimension, with a score of 0,41. More specifically, proxies pertaining to the Family Structure indicator (0.37) report less vulnerability than the ones pertaining to the Gender indicator (0.44).

4.3.2.3.3.2 Economic Dimension

In the Economic Dimension the Attica Region present an average performance (0.48), to which the Wealth and Socio-economic status indicator (0.44) contributes with a better result if compared with the Primary sector indicator (0.52).

4.3.2.3.3.3 Human Capital Dimension

Also in the Human Capital Dimension the Attica Region has an average score (0.49), where Health Services (0.44) show better performances if compared with Educational Level (0.53).

4.3.2.3.3.4 Environmental Dimension

In the Environmental Dimension the Attica Region totalises a score of 0.52. By inquiring the single Indicators in details, it is possible to state that the highest vulnerability is registered in the Residential Property area (0.62) while the best result is obtained in the Land Use and Land Coverage area (0.43).

4.3.3 Discussion

The implementation of ReSVI Index in the three Pilot Sites where data were made available by PS Coordinators (PS3, PS4 and PS5) allowed for showcasing the operationalisation of the Index in three different context and through the selection of different assets in terms of units of analysis (i.e., their numerosity and hierarchical characteristics).

ReSVI is conceived as an instrument to relatively assess the level of vulnerability of an inquired community; this first implementation within FirEUrisk, however, suffered from the lack of availability

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of data in a broader variety of Proxies and Indicators, across all the three Pilot Sites. Challenges related with the data collection process constituted indeed the most relevant shortcoming of the instrument, since data could belong to different fields of expertise, areas of competence and, ultimately, to different institutions. This problem should be partly overcome in future applications of ReSVI by collecting qualitative data (e.g., self-assessment analysis) thanks to the engagement of local stakeholders and institutions. The selection of relevant Indicators and Proxies, as well as the definition of their "orientation" (i.e., their contribution to the overall level of vulnerability, either increasing or decreasing) has been a limited but significant example of self-assessment process conducted within the implementation of ReSVI in the framework of FirEUrisk.

The combination of quantitative and qualitative methods to assess societal vulnerability at a local level has been proven effective also in previous research done on similar fields.

The weighted index allows for a more refined analysis, tailored on the specificities of the inquired area. On the other side, it brings into play less Indicators and Proxies, as some of them were deemed as non-relevant during the initial assessment phase. This report presented both versions, when meaningful, so to fully appreciate the differences, as well as to better represent strengths and weaknesses of both versions of the instrument.

Another open issue is represented by the possibility to involve communities in a peer-to-peer analytical process, instead of limiting the application of the instrument to a specific Pilot Site, i.e., to a relatively homogeneous and delimited territory. The possibility to compare communities one against the other, across different Pilot Sites/contexts, rely upon the capability to set up a common pool of data, or to define a shared approach to compare different sets of data produced because of parallel self-assessment processes.

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5. Societal Vulnerability and Resilience Assessment – A focus on defining and mapping the Wildland-Urban Interface across Europe[24]

This section provides an overview of concepts and methodologies related to wildland-urban interface (WUI) mapping and presents the results of WUI mapping activities in the context of FirEURisk. WUI mapping is a sub-task of WP1.2.2 which complements the analysis of societal vulnerability detailed in the previous chapter and narrows the spatial focus of subsequent analyses to human settlements that are most likely to be exposed to fire hazard. The mapping products detailed below serve dual purposes. First, they are stand-alone geodatabases which contribute to project deliverables; and second, they serve as inputs to analyses of ecological vulnerability at the scale of the European territory (ET) within WP1.2.3 of FirEURisk. As such, they are among the building blocks of the integration framework of the project.

5.1Conceptual framework – An introduction to Wildland-Urban Interface

One of the focal points of societal vulnerability to wildfires is the wildland-urban interface (WUI), which is defined as the area or contact zone where human settlements are adjacent to or interspersed with flammable vegetation (Radeloff *et al.* 2005). The WUI is widespread (Bar-Massada *et al.* 2014) and has been expanding in recent decades in many countries (Radeloff *et al.* 2018; Godoy *et al.* 2022). This, in turn, has increased the exposure of settlements and infrastructure to wildfire activity, thereby contributing to increased wildfire risk. Since the first decade of the 21st century, there has been a consistent effort to map the WUI to identify hotspots of wildfire exposure in different regions. As a result, WUI maps are available, for example, in the US (Radeloff *et al.* 2005, 2018; Theobald and Romme 2007; Carlson *et al.* 2022), and across Europe at continental (Modugno *et al.* 2016), and regional (Lampin-Maillet *et al.* 2010; Alcasena *et al.* 2018; Mitsopoulos *et al.* 2020; Del Giudice *et al.* 2021) scales. However, the current WUI map of Europe (Modugno *et al.* 2016) depicts WUI patterns at a coarse spatial scale, as it is based on CORINE land cover data that has a minimum mapping unit of 25 ha. The current European WUI map, therefore, does not capture small settlements or individual buildings, and consequently cannot highlight individual settlements that are potentially exposed to wildfires (while it may provide insights about coarse WUI patterns in a given region or state). As an alternative, fine-grain WUI maps can provide very valuable information for decision making but are often constrained by a lack of sufficiently detailed input data on settlement patterns for large areas. Recent developments of high-resolution remote-sensing products that focus on built-up areas in general (Pesaresi *et al.* 2016; Corbane *et al.* 2021), and individual building locations in particular (Microsoft Open Source 2022), provide an opportunity to create such fine-grain WUI maps (Bar-Massada 2021; Carlson *et al.* 2022). However, a continental-scale fine-gained map of the WUI across Europe is still lacking. This study was motivated by this gap. Our objective, therefore, was to create the first wall-to-wall map of the European WUI at a high resolution. Given FirEURisk's focus on two

[24] This chapter is based on the work and results achieved by the A1.2.2 working group and it is edited by the following authors of this deliverable: UH (Avi Bar-Masada).

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separate spatial scales, we generated two types WUI maps: one for each pilot site, and one for the entire European territory (ET).

5.2Methodology for defining and mapping WUI across Europe in FirEURisk

5.2.1 Built-up and Vegetation Data

Built-up data was obtained for Europe from two sources:

1. Individual building locations were obtained for each pilot site based on existing geodatasets. Where building data did not exist, we manually digitized them based on high resolution satellite data available via the Bing Maps map service in QGIS.
2. For mapping the WUI at ET scale, the 2019 World Settlement Footprint dataset (WSF; (Marconcini *et al.* 2020)) was used. This dataset was generated by automated interpretation of 10-m resolution Sentinel-1 and Sentinel-2 satellite imagery, and each pixel is either built-up or not. Next, vegetation data was gathered from the 2020 European Space Agency (ESA) global land cover product (Zanaga, Daniele *et al.* 2021). This dataset is a classification of the same 10-m Sentinel-1 and Sentinel-2 satellite imagery, in conjunction with auxiliary data, into 11 land cover classes. This dataset was reclassified into two classes: woody vegetation classes ('forests' and 'shrublands', "1") and others ("0"). Hence, the research focused on fire hazard only from woody vegetation, regardless of species identity and fuel characteristics.

5.2.2 Wildland-Urban Interface Mapping

The most common approach for WUI mapping distinguishes between WUI intermix and interface classes (Radeloff *et al.* 2005). An intermix WUI is a unit area that: [1] comprises enough buildings exposed to wildfire risk; and [2] contains or is directly surrounded by sufficient amounts of flammable vegetation. An interface WUI is a unit area that contains buildings that are not directly surrounded by flammable vegetation yet is within a relatively short distance from a contiguous patch of flammable vegetation which can produce firebrands.

To map the WUI, the parameters of the existing point-based WUI mapping approach were modified (Bar-Massada *et al.* 2013), which is based on the original US WUI mapping approach (Radeloff *et al.* 2005).

The new approach adapts the 10 m-cell grid of the underlying datasets and includes the following steps:

1. Including all cells within 100 m of a building point (in the PS case) or a built-up cell (in the ET case) as candidate WUI locations, regardless of the housing density within (and around) them in order to identify all built-up areas that are potentially at risk.
2. Calculating the percent cover of woody vegetation within a 500 m radius (Bar-Massada *et al.* 2013; Carlson *et al.* 2022) around candidate WUI location cells; if woody cover was greater than 50%, these cells were mapped as 'intermix WUI'.
3. Identifying patches of woody vegetation that were larger than 5 km^2 (Radeloff *et al.* 2005).

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4. Identifying all candidate WUI locations that were within 600 m to large vegetation patches; these cells were mapped as 'interface WUI'. The choice of 600 m reflects findings about the approximate *median* value of maximum travel distances of flying embers (Storey *et al.* 2020). This threshold differs from the previously used distance of 2,400 m (Argañaraz *et al.* 2017; Radeloff *et al.* 2018; Carlson *et al.* 2022), which reflects *maximum* travel distances. The result of this process is a WUI map at either PS scale (if built-up information was based on individual buildings; five WUI maps overall) or ET scale (when the input was the WSF dataset; one WUI map for the entire ET). Based on these maps, we quantified the overall extent and the spatial distribution of interface, intermix, and total WUI at the country level for each country in our study area. We also calculated the variation in WUI cover within countries, by overlaying a map of statistical regions at NUTS-3 level obtained from Eurostat, the EU's statistical agency. The WUI maps generated here are available for download in the project's data repository.

5.3Results of Defining and Mapping WUI Across Europe in FirEURisk

5.3.1 Results Overview

The total area of the WUI in Europe in 2020 was about 363,000 km^2, or 7.4% of the land area. Of that, 169,312 km^2 was intermix WUI (46.6%), and 193,974 km^2 was interface WUI (53.4%). There were considerable differences among countries in the WUI's relative cover and the composition of intermix vs. interface WUI (Figure 15, Table 5). With 23% of its area in WUI, Lichtenstein had the highest relative WUI cover in Europe, followed by Slovenia (16.13%) and Switzerland (15.67%). France, the largest country we analyzed, had the highest absolute WUI area (38,288 km^2 of intermix, 26,291 km^2 of interface). Malta (0.02%) had the smallest proportion of WUI area in Europe, followed by Ireland (0.95%) and Norway (2.08%). Twenty-five countries had more interface than intermix WUI, and 11 countries had more intermix than interface WUI (Table 1). Kosovo (2.86 times more interface than intermix), Ireland (2.38), the United Kingdom (2.1), and Denmark (2.03) had more than twice the area of interface WUI. In contrast, Malta had no interface WUI at all, Finland had almost 2.7 times more intermix WUI, and Sweden 1.66 (Table 1). There was considerable variation in the proportion of WUI across Eurostats NUTS-3 zones within countries (Figure 16). For example, proportions of WUI across 401 German NUTS-3 zones ranged from zero (Straubing) to 87.8% (Herne). In Bulgaria, on the other end, proportions of WUI tended to be low across its 28 NUTS-3 zones, as the range was between 0.01% (Yambol) and 10.9% (Kardzhali).

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Table 7: Country-level statistics of interface and intermix WUI

Country	Interface WUI (km^2)	Intermix WUI (km^2)	Interface WUI (%)	Intermix WUI (%)	Total WUI (%)	Interface/ Intermix
Albania (AL)	979.92	1,340.01	3.40	4.65	8.06	0.73
Austria (AT)	6,008.86	5,408.89	7.16	6.44	13.60	1.11
Belgium (BE)	2,520.08	2,030.62	8.22	6.62	14.84	1.24
Bulgaria (BG)	2,242.53	2,043.75	2.02	1.84	3.86	1.10
Croatia (HR)	2,042.15	3,253.81	3.61	5.76	9.37	0.63
Czech Republic (CZ)	6,056.36	3,171.05	7.68	4.02	11.70	1.91
Denmark (DK)	1,293.97	634.60	3.00	1.47	4.47	2.04
Estonia (EE)	1,750.16	1,343.90	3.86	2.96	6.82	1.30
Finland (FI)	4,420.46	11,963.06	1.31	3.54	4.85	0.37
France (FR)	38,288.36	26,291.31	6.98	4.79	11.76	1.46
Germany (DE)	26,739.93	15,602.13	7.48	4.36	11.84	1.71
Greece (EL)	3,686.76	5,378.42	2.80	4.08	6.88	0.69
Hungary (HU)	2,999.58	1,792.57	3.23	1.93	5.15	1.67
Ireland (IE)	464.51	194.40	0.67	0.28	0.95	2.39
Italy (IT)	16,652.09	26,744.35	5.54	8.90	14.44	0.62
Latvia (LV)	1,927.33	1,149.38	2.98	1.78	4.76	1.68
Liechtenstein (LI)	22.11	14.71	13.81	9.19	23.01	1.50
Lithuania (LT)	2,455.83	1,230.52	3.78	1.90	5.68	2.00
Luxembourg (LU)	267.23	116.67	10.29	4.49	14.79	2.29
Macedonia (MK)	504.27	354.58	1.98	1.39	3.38	1.42
Malta (MT)	0.00	0.07	0.00	0.02	0.02	
Montenegro (ME)	197.93	261.39	1.43	1.88	3.31	0.76
Netherlands (NL)	2,116.34	1,166.55	5.66	3.12	8.78	1.81
Norway (NO)	2,707.07	4,025.90	0.84	1.25	2.09	0.67
Poland (PL)	19,164.02	10,682.26	6.14	3.42	9.57	1.79
Portugal (PT)	4,253.39	3,827.78	4.79	4.31	9.10	1.11
Romania (RO)	5,799.70	3,932.32	2.43	1.65	4.08	1.47
Serbia (RS)	2,691.09	2,647.14	3.47	3.42	6.89	1.02
Slovakia (SK)	2,158.91	1,306.22	4.40	2.66	7.07	1.65
Slovenia (SI)	1,262.66	2,006.63	6.23	9.90	16.13	0.63
Spain (ES)	11,444.37	10,888.95	2.31	2.19	4.50	1.05
Sweden (SE)	5,348.11	8,874.27	1.19	1.97	3.16	0.60
Switzerland (CH)	4,006.25	2,463.28	9.70	5.97	15.67	1.63
United Kingdom (UK)	8,850.20	4,206.53	3.62	1.72	5.34	2.10

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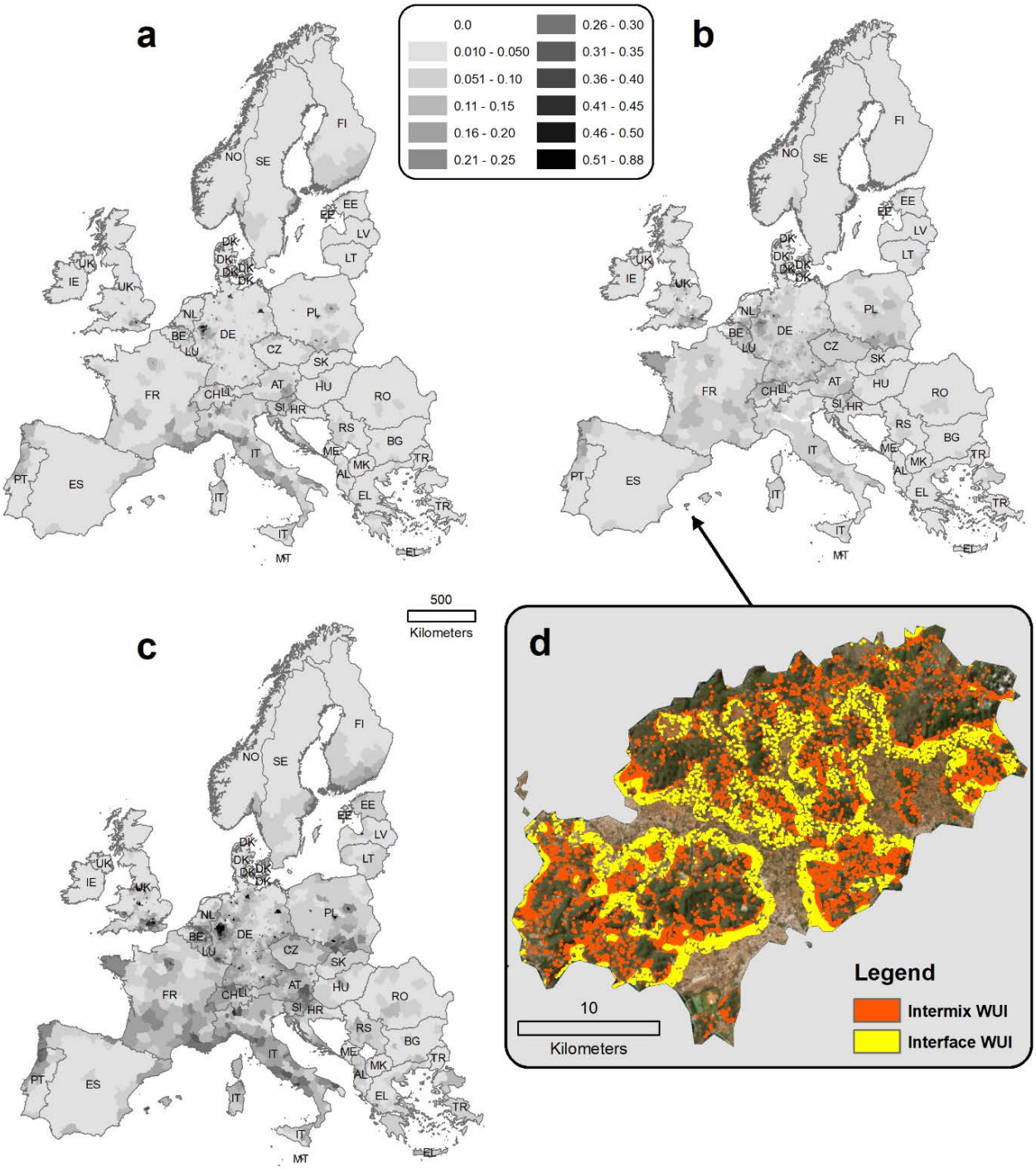


Figure 8: Proportion of WUI in NUTS-3 zones across Europe, 2020, for intermix WUI (a), interface WUI (b), and total WUI (c). (d): high-resolution WUI map of the Island of Ibiza, overlaid on top of a true-colour satellite image (where dark colours depict wildland vegetation patches). See country abbreviations in Table 5

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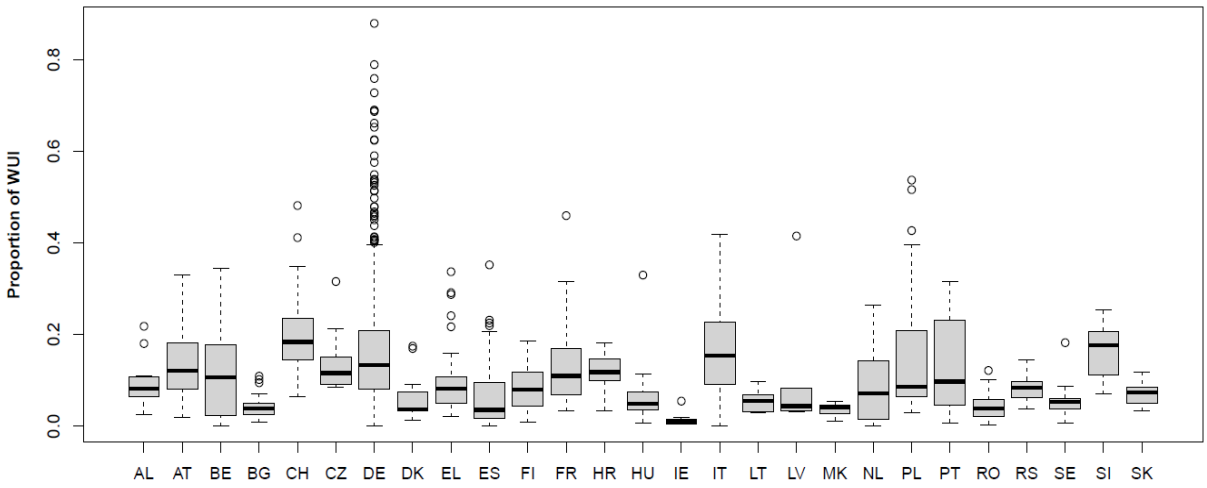


Figure 9: The distribution of WUI proportions at national scales, for countries with at least five NUTS-3 zones. The thick horizontal line depicts the median, and box outlines depict the 25%-75% range. Whiskers reflect 95% confidence intervals and circles are extreme values. For country abbreviations, see Table 5.

5.3.2 Discussion

The chapter presents the first wall-to-wall high-resolution map of the WUI in Europe, and five high-resolution WUI maps at individual pilot sites, based on individual building locations. This approach expands the geographic coverage of previous high-resolution maps in Europe, which were limited to specific countries or sub-regions (Lampin-Maillet *et al.* 2010; Alcasena *et al.* 2018; Del Giudice *et al.* 2021), and the spatial resolution compared to a previous wall-to-wall map (Modugno *et al.* 2016).

WUI is a prevalent land cover type in Europe, as it covers 7.4% of the surface area (compared to 16.2% for the US, but using a different algorithm; (Carlson *et al.* 2022)). However, the amount of WUI varies considerably among countries, from almost no WUI in Malta to almost one-quarter of the country's area being a WUI in Lichtenstein. There was also a large variation in WUI proportion within countries, especially in larger countries with diverse landscapes, such as Germany, where forest cover varies greatly among sub-regions. These considerable variations in WUI patterns stem from inherent differences within and among countries in both settlement patterns and vegetation configuration across landscapes. In turn, they highlight the complexity of designing consistent wildfire mitigation activities (such as fuel treatments in and near the WUI) using a top-down approach, as they should be custom-tailored to the specific characteristics of a given landscape or even a single locality. For example, in Nordic countries the majority of the WUI is driven by scattered dwellings surrounded by large contiguous swaths of forested lands, which results in a much larger proportion of intermix WUI. In contrast, in the UK and Ireland most of the WUI is characterised by clustered development adjacent to smaller forested patches, and consequently they have more than double the area of interface WUI compared to intermix WUI. These two main WUI types require inherently different approaches for fuel treatments in order to reduce fire hazard: intermix WUI will benefit from treatments in the home-ignition zone, whereas interface WUI can also be protected by creating a buffer zone between settlements and adjacent forests. Hence the map we present here offers an overview of WUI patterns

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across Europe, which should be complemented by local-scale analyses that can provide concrete management recommendations for reducing wildfire hazard.

When comparing the proposed WUI maps to others, it is important to remember that any WUI map is heavily affected by the mapper's choices of specific thresholds and parameters. Here, the choice was for a categorisation of wildland vegetation that focused on woody vegetation and did not include grassland vegetation. This choice has been made by others before (Kaim *et al.* 2018) and reflects a more restrictive view of the WUI as being related solely to forest and shrubland ecosystems.

Focusing on woody vegetation is the outcome of two reasons: they tend to produce more extreme fire behaviour (compared to grasslands), and they are considerably more expensive to manage pre- and post-fire. This choice is also reflected, for example, in the official guidelines of forest management agencies in Catalunya which describe the WUI explicitly as a forest-urban interface. Beyond this management-oriented decision, there was also a practical consideration for this choice: there were considerable classification errors between grasslands and croplands in the landcover dataset we used (Tsendbazar *et al.* 2021). Including grasslands as wildland vegetation would have created large WUI areas in agricultural regions with little natural vegetation. As a result, the exclusion of grassland vegetation in some agropastoral lands may lead to an underestimate of the WUI area, where flashy fuels cover large portions and play a prominent role in risk transmission (Salis *et al.* 2022). In contrast, this case included all types of woody vegetation classes as wildland vegetation, regardless of their ability to support wildfire spread. In terms of fire risk assessment, this may lead to an overestimate of potential settlement exposure to wildfires, in areas where the flammability of the dominant woody vegetation is low.

This analysis provides the first detailed yet expansive depiction of WUI areas across Europe. The WUI problem in Europe is expected to increase due to ongoing land abandonment in Mediterranean and East European countries (which increases vegetative cover around settlements), more secondary home development in rural areas (which pushes settlements into wildlands), and changes in fire regimes including the introduction of wildland fires into previously non-fire prone areas. These processes, among others, are increasing the exposure of people and property to wildfires, and there is urgent need to inform policy decisions that may reduce this risk by better land use planning. These new WUI maps may offer useful information to achieve this aim.

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6. Environmental Vulnerability and Resilience Assessment – A Focus on Ecological Vulnerability[25]

Wildfires affect most ecosystems worldwide, and major attention has been devoted to quantifying burned area (Giglio et al. 2018, Lizundia-Loiola et al. 2020) and fire drivers (Ruffault et al. 2020) to target firefighting and management strategies. However, short and long-term impacts of fire on ecosystems can be very variable depending on key characteristics of these ecosystems, bringing up the concept of ecological vulnerability over exposed areas. For Ecosystem, fires rapidly consume leaves and fine wood, then affecting thicker parts of trees, litter, and potential soil carbon stocks through smouldering combustion (van der Werf et al. 2010). Biomass combustion then affects vegetation survival by consuming vessels necessary for sap flow and water/gas exchanges and cells able to regenerate leaves (Bär et al. 2019). When affecting vegetation, related ecosystems properties are modified as carbon stocks (Seidl et al. 2014) , biosphere/atmosphere interactions (van der werf et al. 2010) and subsequent ecological values, as well as the associated habitat for microbial and animal populations (thom and Seidl 2016) . In fire-prone ecosystems, most species developed different strategies to persist fires which can balance losses at the individual, population, community, and ecosystem scales (Pausas 2018). Once affected, vegetation responds to fire through their regeneration strategies, allowing post-fire recovery, with subsequent recovery of habitat and ecosystems functions. Quantifying these potential impacts on ecosystems and the post-fire recovery is a key information for firefighting and fire management strategies to adopt, by targeting the region with the most vulnerable ecosystems potentially being lost or harmed within the years following the disturbance. Ecological vulnerability to fire is however hardly fully assessed in current strategies due to the lack of information that prevents the application of an integrative and conceptual framework to be applied at regional or continental scale.

6.1Conceptual framework – An Introduction to Ecological Vulnerability

6.1.1 Definitions, Concepts, and Integration Scheme of Vegetation Vulnerability

For the ecological vulnerability assessment, and among the definitions proposed in Lei et al. (2014), we adopted the definition of Kasperson and Kasperson (2001,2015), where 'vulnerability is the flip side of resilience'. Resilience is a keystone concept in ecology defined as the ability of a system to anticipate, absorb, accommodate, and recover from a disturbance across time (IPCC 2012). Vulnerability is defined by the potential loss (defined as an integration of ecological values potentially lost after a fire over the exposed area of the disturbance) and the post-disturbance recovery trajectory from the point of actual loss (De Lange et al. 2010). A complete list of terms related to environmental vulnerability appears in Table 8.

[25] This chapter is based on the work and results achieved by the A1.2.3 working group and it is edited by the following authors of this deliverable: IRD (Florent Mouillot), CSIC (Bruno Moreira)

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Table 8: Definitions of exposure, hazard, risk, vulnerability, ecosystem vulnerability, resilience, and habitat

Exposure	**Contact of an organism with a chemical, radiological, or physical agent. Exposure is quantified as the amount of the agent available at the exchange boundaries of the organism (e.g., skin, lungs, gut) and available for absorption.**
Hazard	A threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area.
Risk	Expected losses due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability.
Vulnerability	The degree to which a system is susceptible to, and unable to cope with, injury, damage or harm. Vulnerability is a function of exposure, effect (also termed potential impact, sensitivity), and recovery (also termed resilience or adaptive capacity).
Ecosystem vulnerability	The potential of an ecosystem to modulate its response to stressors over time and space, where that potential is determined by characteristics of an ecosystem that include many levels of organization. It is an estimate of the inability of an ecosystem to tolerate stressors over time and space. It is a combination of community vulnerability with the potential for habitat changes.
Resilience	Ecological resilience can be defined in two ways. The first is a measure of the magnitude of disturbance that can be absorbed before the (eco)system changes its structure by changing the variables and processes that control behaviour. The second, a more traditional meaning, is as a measure of resistance to disturbance and the speed of return to the equilibrium state of an ecosystem.
Habitat	The place occupied by an organism, population, or community. It is the physical part of the community structure in which an organism finds its home, and includes the sum total of all the environmental conditions present in the specific place occupied by an organism. Often a habitat is defined to include a whole community of organisms.

Potential loss is then defined by the ecological value of the ecosystem that can be affected at maximum disturbance effect without any resistance. This requires the definition of values to assign to ecosystems.

We focus here on Ecological values, which can be defined as ecosystem properties related to habitat, and biodiversity (Amador Cruz 2021). **Habitats** relate to the benefit that nature provides to sustain life, including vegetation biomass and structure allowing animal foraging (food resource), movement (connectivity) and nesting (protection). Biodiversity includes all variability of life (organisms, species, populations), their complex interactions and assemblages of communities and ecosystems. There are different scales and measures of diversity from genetic diversity (that may be measure both at

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intraspecific or interspecific level), species diversity (variation within and between populations or communities, different measures such as taxonomic, functional or phylogenetic diversity) to ecosystem diversity (variation within and between ecosystems in habitats, communities and ecological processes). Ecological values then include plants, animals, biogeochemical cycles and soils.

The **coping capacity** relates to the strategies of species composing the ecosystem to withstand, absorb and recover from a disturbance and continue to function (Parsons et al. 2016). The **coping capacity** covers both the concepts of **resistance** and **response capacity** to the disturbance. **Resistance** is a common concept in ecology defined by the capacity of a species to survive and absorb the disturbance so that only a fraction of the potential loss will be lost according to **resistance** strategies. The **actual loss** combines the **potential loss** and the **resistance**. The **response capacity** defines how fast the species will recover after the disturbance. In fire prone ecosystems, it can be decomposed into **recovery rate**, and **regeneration time**. The **recovery rate** is the standard rate of growth of a species, assuming the presence of regenerative material on the site. These can be viable seeds in the soil or the canopy, or viable below or aboveground material able to develop and grow. The **regeneration time** is then the time needed for an ecosystem to get the required source of new individuals, by dispersal or movements. Altogether, the r**ecovery rate** and the **regeneration onset time** will define the **recovery time**, as the time needed to recover the pre-fire species status (biomass). The resilience of the ecosystem is then defined as a combination of specific trajectories of the post-fire recovery, assuming total loss of the ecosystem. The final ecosystem recovery state can be like the pre-fire state when all species experience on-time recovery, delayed when some species regeneration is prevented, reduced when some species regeneration is prevented and no seeders are available in a close by neighbourhood, or higher than the pre-fire state when exotic species are introduced by natural dispersion or restauration and management plans. **Vulnerability** finally combines the **actual los**s and **resilience** of the ecosystem (Figure 10).

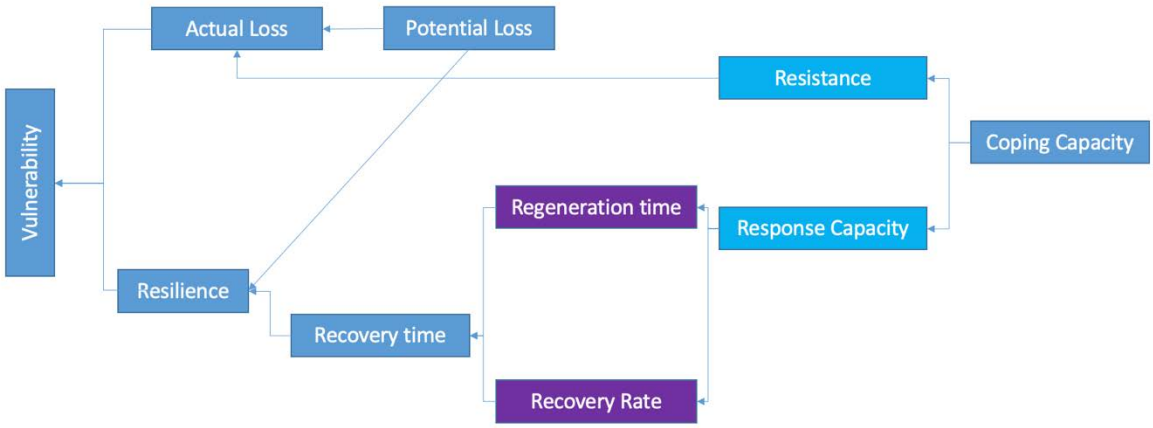


Figure 10: Integration scheme of ecological vulnerability and related concepts.

6.1.2 Modelling Vegetation Vulnerability

Figure 11 illustrates how vegetation vulnerability can be formalised into a temporal trajectory of fire impacts and, post fire recovery. From pre fire state of the plant species composing the ecosystem

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(biomass, tree cover, biodiversity…) and representing the potential loss (*PL)* over the exposed surface to the fire disturbances, the actual loss (*AL)* during the fire occurring at time t_0 can be calculated from the resistance (*RST)* capacity of the system:

Equation 7: Actual Loss Computation

$$AL = PL - RST$$

After the fire (occurring at time t_0), the state of the vegetation remains at state *RST* during the regeneration time (*RGT)* until viable regeneration material is available on site. Once *RGT* is reached, recovery can start following a recovery trajectory *fres.* Resilience (*RES)* can be evaluated as the area under the curve *fres*. Vulnerability (*V*) can finally be quantified as the area over the curve, accounting for both resilience (*RES*) and resistance (*RST)* according to equation 8:

Equation 8: Vulnerability Quantification

$$V = (PL * RT) - RST * \left(RT + \int_{t0}^{RT} fres(t - RGT)\ dt \right)$$

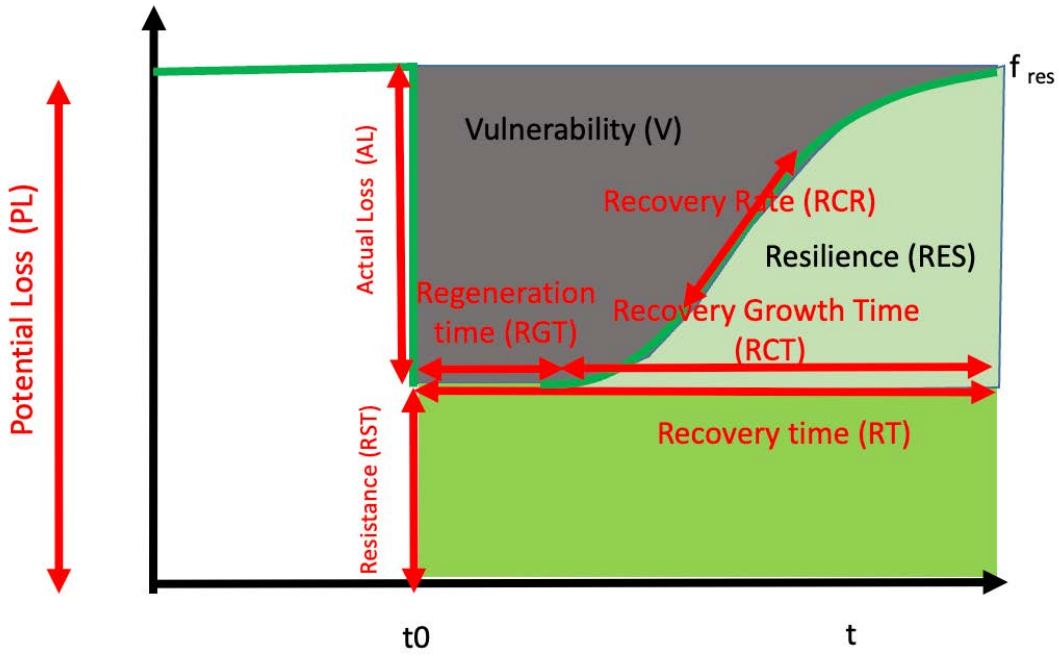


Figure 11: conceptual model quantifying vulnerability (V, grey area) as a function of potential loss (PL), resistance (RST), regeneration time (RGT) and the resilience curve f_{res}, parameterized with recovery growth time (RCT) and recovery rate (RCR).

The recovery function *fres* was chosen as a generic logistic function previously used for post disturbance dynamics (Amani et al. 2022) and applied for multiple functions of ecosystems (Equation 9). f_{res} is a function of time after fire *t,* with parameters related to recovery concepts of Recovery

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growth time (*RCT,* as the time need to fully recover to pre fire ecosystem state) and recovery rate (*RCR*) as the slope the maximum recovery at the inflexion point occurring at time t_i=RCT/2.

Equation 9: Recovery Function

$$fres(t - RGT) = \frac{AL}{1 + e^{-RCR \cdot \left(t - RGT - \frac{RCT}{2}\right)}}$$

6.1.3 Model Parameterization and Application

The main parameters of equations 8 and 9 can be deduced from species functional traits and locally modified according to climate and environment. We distinguish here state variables of ecological values (as biomass, or diversity indices), parameters (mostly species specific), modifiers (affecting equations specific parameters, as climate or management strategies) and exposure (as fire size or intensity). Following the plant strategy classification from Archibald et al. (2019) for fire disturbance, plant species will be classified as resistor, and tolerator at the individual, population, or landscape level. According to this classification, Resistors will have a high resistance (RES) value and a negative regeneration time (RGT) as they regrow from the individuals surviving the fire, then omitting the exponential growth phase before the inflection point. Tolerators at the individual level will have a low resistance value (RST) and a negative regeneration time (RGT) as they regrow from resprouting of their belowground organs and experience a fastened early recovery rate. Tolerators at the population level will have a low resistance value (RST), and low regeneration time (RGT) as they regenerate from seeds surviving the disturbance, allowing for a direct start of the growing phase. Tolerators at the landscape level will have a low resistance value (RST) and a higher regeneration time (RGT) depending on the size of the fire and seed dispersal strategies allowing for new seedling to colonize the site.

This species classification will be based on species traits related to fires (Pausas et al. 2018). Resistance will be mostly related to bark thickness. Regeneration time will be based on the species resprouting ability (basal from bud bank and storage organs or epicormic), or seedling establishment (dependant on seed traits as mass, pericarp thickness, pubescence, seed persistence in soil and canopy – serotiny mostly associated to needleleaf species in Europe, seed resistance to heat or stimulate by smoke cues, and dispersal organs as wings, or pappus).

Environmental conditions will finally affect resistance (RST), regeneration time (RGT) and recovery rate (RCR). Among others, time since last fire directly affects tree age and in turn resistance (RST) (Gonzalez et al. 2007, Hood et al. 2018), but also the viable seed bank availability based on the vital attribute model from Noble and Slatyer (1980), stating that viable seed are only available when mature individual are present or viable seeds could persist in the soil seed bank (seed longevity). In turn time since last fire (a proxy to tree age for seeders) combined with age of maturity (a species trait from BROT2.0) will affect regeneration time (RGT), so that cascading effects might apply with recurrent and short fire intervals (Ibanez et al., 2022). Fire size will drive the distance to unburned individuals providing seeds through dispersion (located outside the burn patch) and in turn the regeneration time for tolerators at the landscape level. Management strategies (through human-driven plantations after fires) will act as a similar process as widespread seed dispersal in accelerating the regeneration time.

Figure 10 indicates plant traits and environmental constraints affecting the generic resistance (RST), regeneration time (RGT) and recovery rate (RCR) from equation 8. in turn the overall vulnerability (V)

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would not be independent of fire exposure, as exposure (fire size and fire intensity) would actively influence regeneration time (RGT) and resistance (RST).

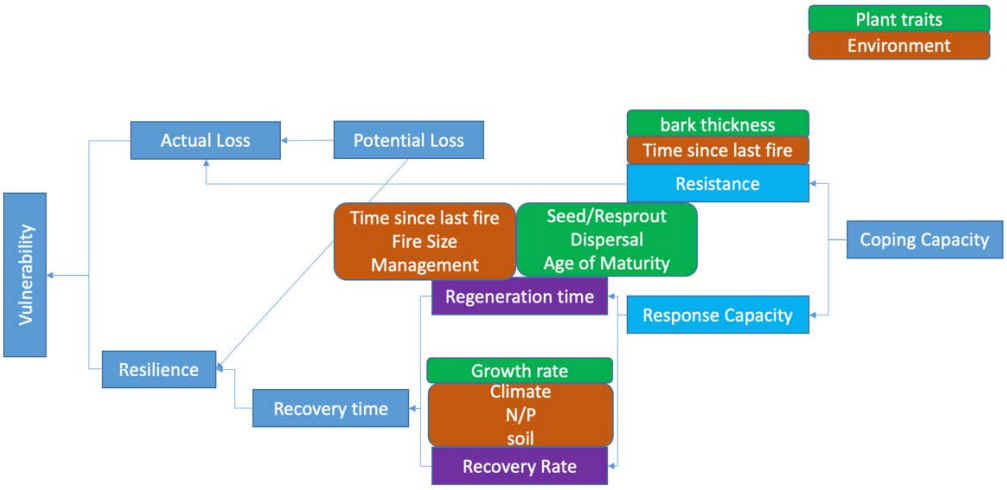


Figure 12: Integration scheme of ecological vulnerability and related concepts with input parameters (plant traits in green) and environmental modifiers (in brown) affecting resistance, regeneration time and recovery rate of vegetation.

6.1.4 From Vegetation to Ecological Vulnerability

Post-fire vegetation dynamic is the keystone information driving the overall ecological values as biomass, water and carbon fluxes, and biodiversity including animals (Figure 20). Soil information (field capacity for available water used by plants, nitrogen, and phosphorus content) is a potential local modifier of the recovery growth rate (RCR) and potentially the first variable in the cascading chain of ecological to be affected by fires (Cole et al. 1990). Fires affect soil nitrogen and phosphorus budgets by volatilization processes during combustion of leaves and wood (cf review Abgeshie et al. 2022). Nitrogen is almost fully emitted to the atmosphere while phosphorus is partly deposited in ashes. These elements are lost for ecosystem and litterfall ensuring the cycling of these elements will be disrupted by fires. Post fire vegetation regrowth will use soil nutrients while a reduced recycling though litter fall will happen, potentially leading to post fire nutrient depletion at the ecosystem scale. Atmospheric nitrogen deposition or fixation by leguminous species (Arianoutsou & Thanos 1996), and phosphorus generated from pedogenesis can compensate fire losses within few years, while erosion might affect phosphorus ash deposition and soil field capacity. They have to be quantified as a driver of vegetation dynamic, particularly for recurrent and short interval fires potentially significantly affecting vegetation recovery rate (RCR).

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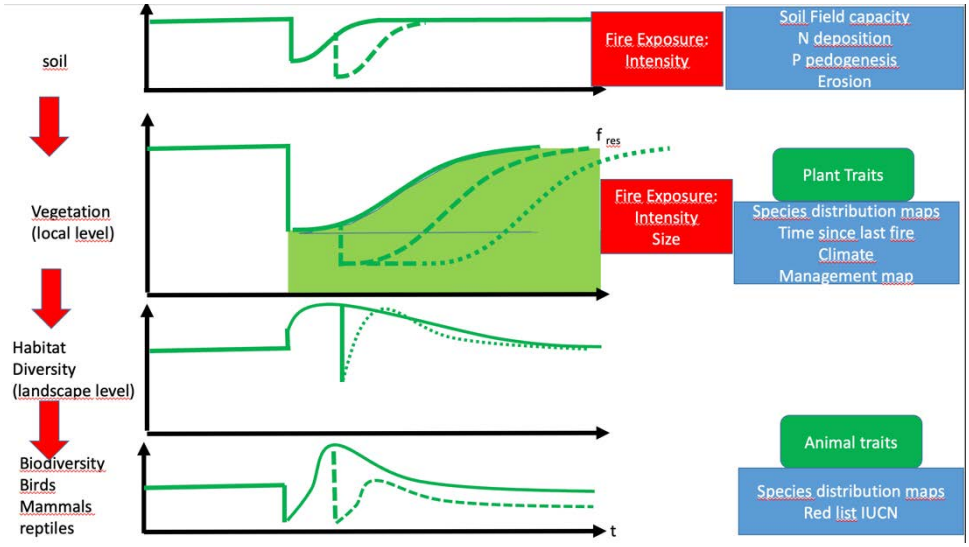


Figure 13: Causal relationships and processing chain for ecological vulnerability based on soil, vegetation, habitat and overall biodiversity in fire prone ecosystems for ecological vulnerability assessment. Post-single fire trajectories are illustrated in plain green line. Post-second fire trajectories are illustrated in large-dotted line (no additive effect) or fine-dotted line (additive effect influencing regeneration time RGT). Cf Ibanez et al. (2022) for potential conceptual additive effects after recurrent disturbances. Required input databases are listed.

The biodiversity of birds, mammals and reptiles is affected by fires mostly by changes in habitats generated by fires (Herrando and Brotons 2002, Tingley et al. 2016). As they can easily move across landscapes, animals are hardly directly affected by fires, and can easily colonize burned areas after the fire (Jaquet and Prodon 2009). However, each species is associated to a given habitat according to its foraging and nesting habits. Assessing post-fire animal dynamic is then dependant on habitat description (Tews et al. 2004). Habitat loss and post fire recovery will be assessed through landscape composition changes in vegetation based on the extent of the disturbance and the subsequent vegetation recovery. Landscape diversity based on the relative composition of bare land, herbaceous, shrubs and trees will be the major descriptor. Animal biodiversity loss will be assessed as a function of habitat loss, animal traits related their habitats, with rarity indices associated with their level of protection and disappearance threat. While fire effect on biomass is systematically negative, habitat diversity highly depends on its initial state and the extent of the fire Small fires in large fire patches can increase habitat (and subsequent animal) diversity while large fires will homogeneize the landscape pattern in highly fragmented areas, small fires can fully eliminate small forest patches and reduce habitat diversity. In turn, we integrate post-fire vulnerability to be potentially negative when post fire conditions for an ecological value is higher than the pre-fire state, as identified in Rocez-diaz et al. 2022.

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6.2 Methodology for Ecological vulnerability assessment in FirEURisk: Datasets for ET Applications

Input variables required for the modelling chain of ecological vulnerability assessment at 1 km resolution will be based on existing maps and databases. They are listed below by categories.

6.2.1 Environmental Variables

Environmental variables refer to abiotic variables affecting vegetation dynamic and recovery rates.

6.2.1.1 Soil maps

Tree growth and ecosystem productivity is mostly limited by soil water shortage during summer months, related to climate and soil available water content (AWC). We use the subsoil et topsoil AWC at ET scale based on soil texture, soil depth and rock fragment content (Figure 21) to simulate an average summer drought index used as a local modifier for the recovery rate (RCR). We use daily climate data from ERA5land.

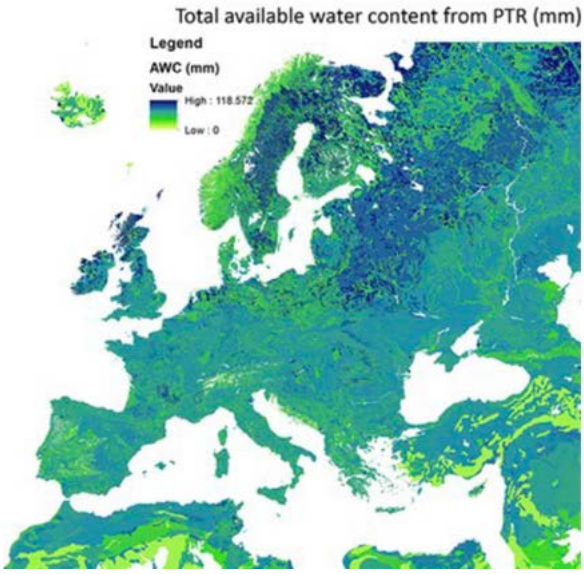


Figure 14: Available water content (AWC) map (in mm). Source: https://esdac.jrc.ec.europa.eu/content/european-soil-database-derived-data

6.2.1.2 Soil fertility from N & P content and inputs

Soil N and P content is available from JRC for EU countries only (Figure 22) refer to top soil N and P concentration in soils and will used a standard fertility status without disturbance.

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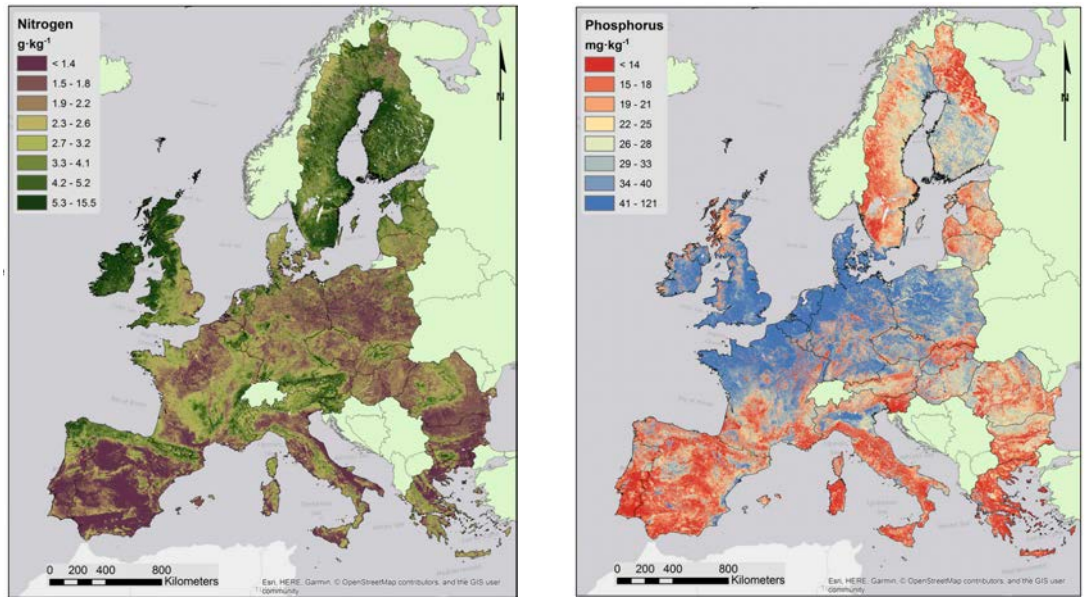
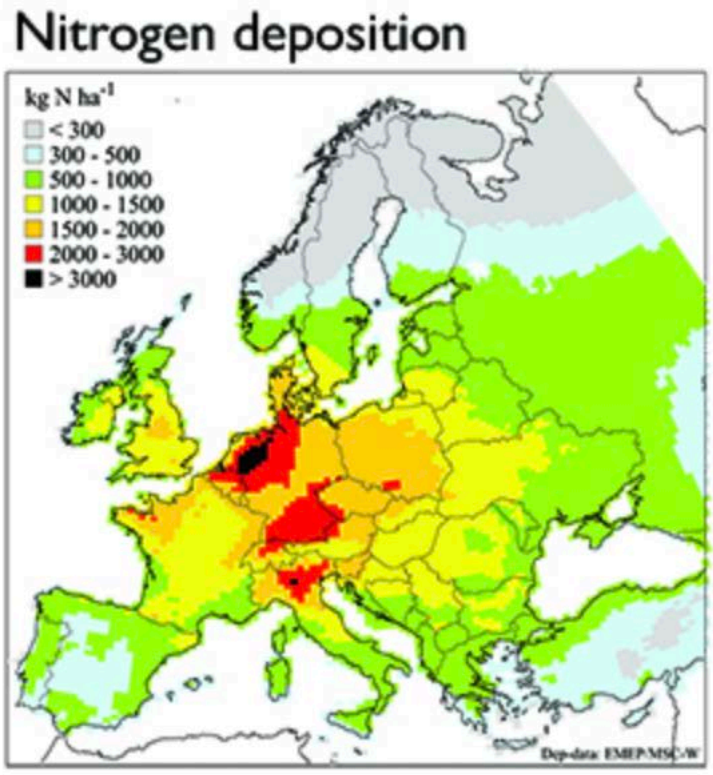


Figure 15: N (left panel) and P (right panel) soil content over ET.

Post fire recovery rate (RCR) will be affected by soil fertility based on the standard soil N/P content, N and P loss from Leaf Area Index and C/N C/P ratio in leaves (Plant trait database TRY Katjes et al.), from volatilization and wind/water post fire erosion potentials (see below). Post fire N/P stock recovery will be based on N Atmospheric deposition map and N fixing plant distribution (Tedersoo et al. 2018) (Figure 23).



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Figure 16: Atmospheric N deposition map (gN.ha-1) over ET. Source: https://www.syke.fi/en-US/Current/Sciencepolicy_cooperation_has_improved_a%2859833%29.

6.2.1.3 Erosion maps

Water and wind erosion can affect bare ground after fires, affecting soil water retention potential and N/P deposition from ashes. They dependent respectively on topography, soil texture and wind speed.

The water soil erosion map and wind erosion susceptibility maps (Borelli et al. 2014) will be used (Figure 15).

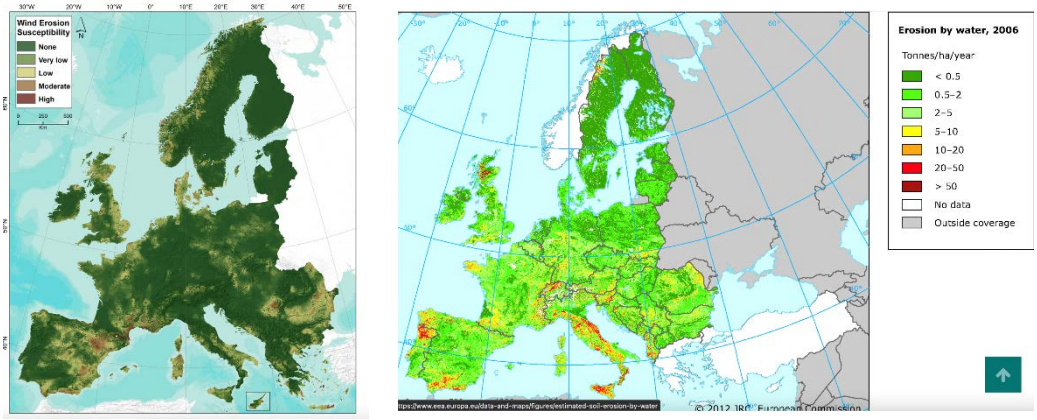
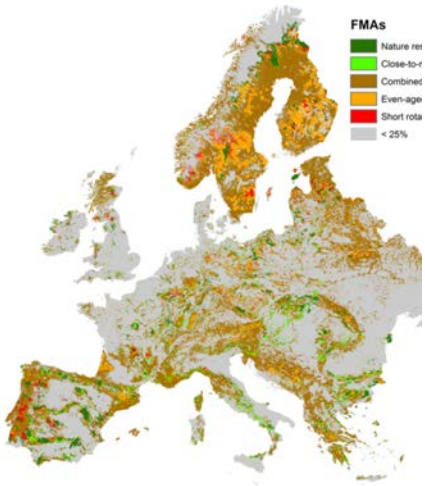


Figure 17: Wind erosion map (left panel) and water erosion map (right panel). Sources: https://esdac.jrc.ec.europa.eu/content/Soil_erosion_by_wind and https://www.eea.europa.eu/data-and-maps/indicators/soil-erosion-by-water-1/assessment.

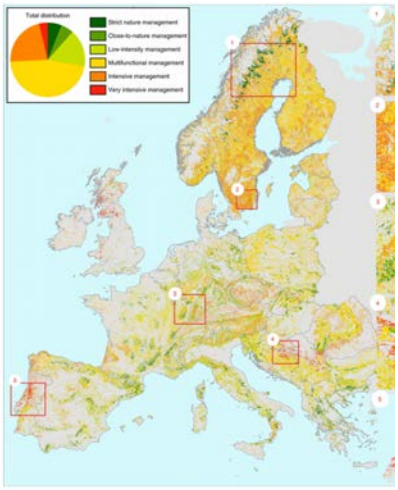
6.2.1.4 Ecosystem Management map

Humans might play a significant role in post fire forest recovery by stimulating (or preventing) plantation or burned wood collection. We use from management maps from Hengenveld et al. (2012) and Nabuurs et al. (2019) over ET to affect the regeneration time (RGT) as a local modifier of regeneration (Figure 16)

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Hengenveld et al. (2012)



Nabuurs et al. (2019)

Figure 18: Forest management maps over European Territory.

6.2.1.5 Fire history map

Fire history and time since last fire will be used a modifier for regeneration time (RGT). This information can be built over ET from global remote sensing burned area at 500m (MODIS MCD65A1, https://modis-fire.umd.edu/ba.html), 250m (FireCCI, https://climate.esa.int/fr/projects/fire/) over the 2001-2020 period, or at finer resolution since 2012 from EFFIS (https://effis.jrc.ec.europa.eu/). As tree maturity is usually reached after 15 years, We mostly focus the analysis on coarser scale resolution, and acknowledged to accurately capture burned area above a fire size threshold of 250ha. The daily burned date information at the pixel level will be used to deduce the time since last fire (in days). Combined with time since last fire, We also use fire size as a modifier for regeneration time, as seeder species will take more time to colonize a large fire than a small one. The pixel aggregation from Laurent et al. (2018) will be used for the fire patch event database.

6.2.2 Vegetation

Vegetation will be key driver of post fire habitat dynamic and subsequent biodiversity and ecosystem values for vulnerability assessment. Forest species distribution will be derived from the European Atlas (https://forest.jrc.ec.europa.eu/en/european-atlas/atlas-data-and-metadata/) (Figure 17).

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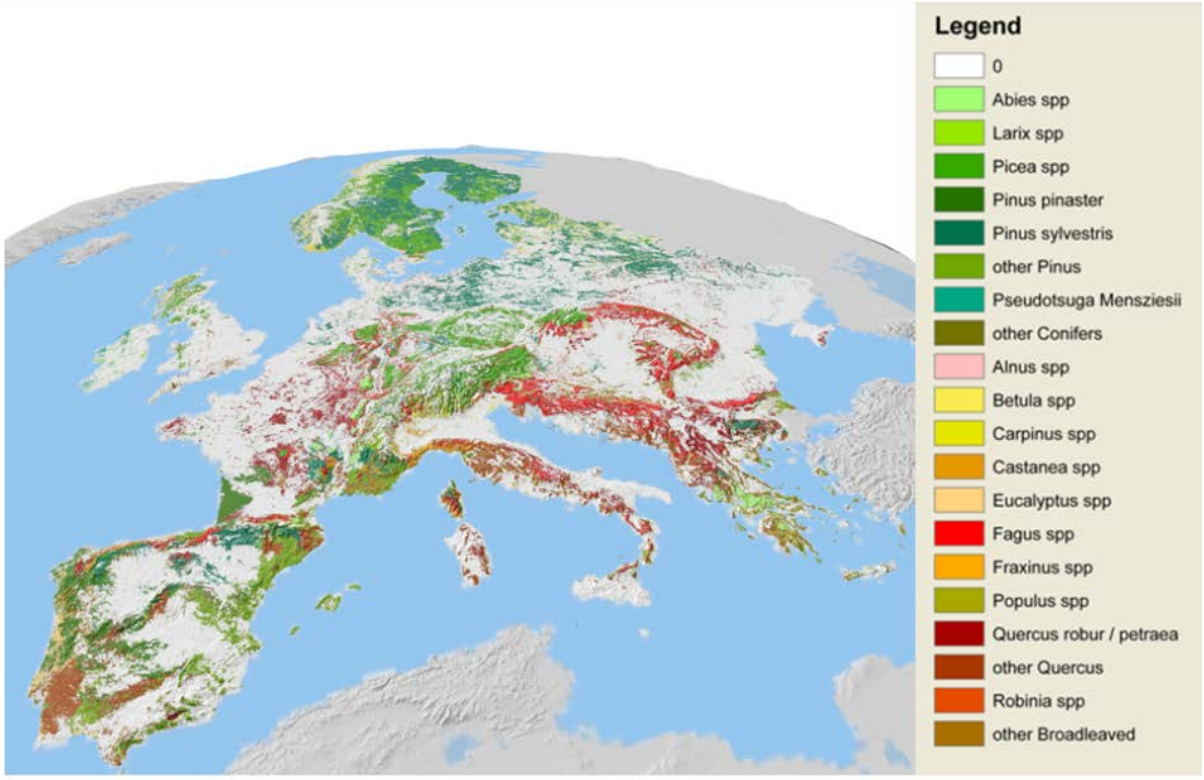


Figure 19: European map of dominant tree species distribution. (European forest Atlas).

In addition, forest biomass maps as an ecological value will be assessed through tree heigh (Potapov et al. 2016, https://glad.umd.edu/dataset/gedi), tree cover (Hansen et al. 2013, https://data.globalforestwatch.org/documents/tree-cover-loss/explore), and biomass (Santoro et al. 2021, https://globbiomass.org/wp-content/uploads/GB_Maps/Globbiomass_global_dataset.html).

Habitats rather than plant species are usually linked to animal distribution (Barnagaud et al. 2021), as a simpler information of vegetation openness. From vegetation dynamic and recovery rate and time, post fire habitat dynamic will be derived as a function of landcover, disturbance size and time since last fire, as a fraction of open and closed canopy fractions.

Tree species traits related to fire and functioning will be assessed through the fire related plant traits for the Mediterranean basin available as initiated in the BROT2.0 database (Tavsanoglu and Pausas 2018, Pausas et al. 2016, https://www.uv.es/jgpausas/brot.htm), and further assembled in the project, and the global plant trait database relating plant functioning as carbon assimilation, C/N ratios (Kattge et al. 2011, https://www.try-db.org/TryWeb/Database.php).

6.2.3 Animals

Spatially explicit information on animal distribution over the European territory (ET) can be available a difference resolution with more or less adequate accuracy. Based on Fusco et al. (2021) for bird diversity analysis, We use the 1° resolution bird database (http://datazone.birdlife.org/home). We will use the atlas from Sillero et al. (2014) (https://www.seh-herpetology.org/distribution-atlas) for reptiles and amphibians and the european atlas for mammals (https://discovermammals.org/projects/the-2nd-european-mammal-atlas/). The link between

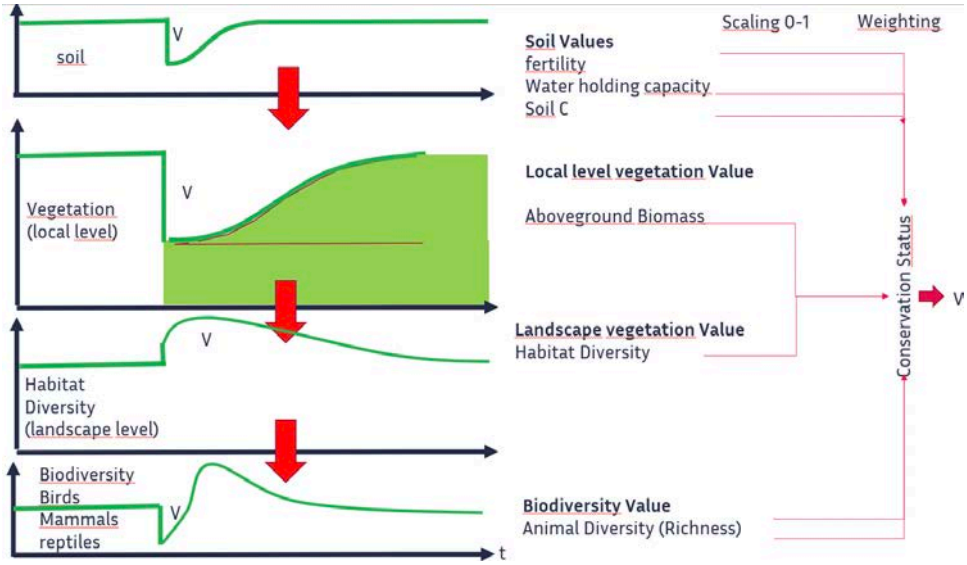
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habitats and animals will be based on their morphological, functional and biogeographical traits, with database of Soria et al. 2021 (COMBINE) for mammals, Tobias et al. 2022 for birds (AVONET), Grimm et al. (2014) for reptiles. These traits illustrate their biographical preferences in terms of habitat and foraging/movement capacities. In order to account for the rarity of species and the conservation priority on Europe, each species will be associated to a score based on the red list classification (https://ec.europa.eu/environment/nature/conservation/species/redlist/trees/geographic_patterns.htm).

6.3 Results: Integration of Ecological Vulnerability Assessment in FirEUrisk

6.3.1 Results overview

Ecological vulnerabilities including soil, vegetation, habitats and animals diversity will be assessed though their actual losses, regeneration time, and recovery rates. Keystone ecological values will be derived for each category (Figure 27), as soil fertility, water holding capacity and Carbone stock, vegetation biomass and fluxes (Net Primary Production NPP, and evapotranspiration ETR), habitat diversity based on fractional cover of forest, shrubs, herbaceous and bare land. Biodiversity, as a critical ecological value, will be assessed through species (taxonomic diversity) and functional (based on traits) richness (Mangeville et al. 2022), rarity (Grenie et al. 2017), and weighted endemism or endangered species to account for threatened species (Diaz et al. 2020, Faroog et al. 2020). Each vulnerability V of ecological values (ev) will be scaled (0-1) and integrated into a single Vulnerability index V, weighted by the level of interest of the region assess by its of protectedness (Natura 2000, National parks, conservation areas or keystone biodiversity areas).



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Figure 20: Conceptual scheme for integrating the vulnerabilities V of ecological values (ev) for soil, vegetation, habitat and biodiversity, into the final VE ecological vulnerability scoring.

6.3.2 Discussion

Assessing ecological vulnerability to fire covers a wide range of inter-dependant processes and theoretically requiring species specific information on fire responses and mechanisms. The objective is to propose a usable tool and processing chain, using easily available and spatially distributed information at various spatial scale from watersheds or regions (Pilot Sites) or European Territory (ET). We based our framework on a mechanistic synthesis of key processes affecting fire impacts and post fire recovery, but kept simple enough for easy and feasible implementation. At ET scale, ecological vulnerability is either considered by its conservation value (based on protectedness) or simple assessment of biomass loss (Forzieri et al. 2021) or tree cover recovery (Senf and Seidl 2022), already providing a first and ecologically-sound assessment index. We provide here a combination of conservation values and impact and resilience assessment of vegetation, but also the impacts on habitat and resulting animal biodiversity. We also aimed at integrating intrinsic (topoclimate, soil fertility) and extrinsic (management intensity) sensitivity/adaptive capacities locally modifying impacts and resilience as used in other frameworks (FireCLIME, Friggens et al. 2019).

The major benefits of this ecological vulnerability assessment tool are:

- Being based on a mechanistic view of fire effects on ecosystems, with a hierarchical cascading effect from soils to vegetation, habitat and overall biodiversity.
- Being simple enough to be implemented from currently available datasets and knowledge at various spatial scales from the watershed to the ET.
- Being potentially updated on a yearly basis to account for yearly changes in forest cover/biomass (from fires, clear cuts, windstorms), and updated time since last fire as a keystone component driving species regeneration capabilities.
- Being used as a management and decision tool by providing species replacement or landscape fragmentation scenarios.
- Being transferable from current climate conditions to future climate projections and subsequent ecosystem functions simulated by dynamic vegetation models, or species distribution models.

The framework is a first version tempting this assemblage of knowledge with limitations in being able to capture all sources of ecosystem functioning post fire dynamic. The limitations mostly include:

- We do not provide a process-based model able to simulate species growth, competition, mortality and associated biogeochemical cycles, but a simplified assessment of ecosystems resistance and recovery following dominant species and functional traits. In turn, the fate of peculiar ecosystems (wetlands, peatlands) and rare/unique species cannot be assessed.

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However, the threatened species map was considered as a conservation value given to specific places

- Processes are not interactive enough to properly provide long term recovery times and soil depletion through dispersal strategies or high erosion rates following extreme climate events. Only a mean value was proposed, not including potential tipping points of ecosystem abrupt changes
- Our framework is mostly focused on negative effects of fires on soils and plants. Habitat diversity is partially accounted for with potential short term post fire positive impact on biodiversity. We did not provide any vulnerability assessment of the absence of fire, potentially homogenizing forest ecosystems and reducing biodiversity, although being a potential usefull assessment for prescribed burning decisions.
- Ecological values related to soil, vegetation and biodiversity were equaly weighted. The framework remains however flexible for adjustments based on expert knowkedge.

The ecological vulnerability map must be understood as the combined direct impact and recovery of a large fire (900ha) on soils, vegetation, habitat and fauna on varying conservation values based on protectedness and key biodiversity areas. It represents, in equivalent years, the integral of ecological values depletion over the time of recovery.

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7. Economic Impacts of Fire – A Focus on Analysis of Economic Vulnerability of Natural and Human Capitals and proposal of an Integrated Capitals Approach to wildfire vulnerability[26]

This section proposes an economic analysis of natural, manufactured, and human capital affected by wildfires by tailoring it into the "Vulnerability" component of the risk model proposed by the FirEUrisk consortium. It addresses the potential losses caused by wildfires seen as a combination of assets manufactured by humans, lives, damages to natural capital and ecosystem services that can be economically valued, suggesting also how to consider non-marketed values that cannot be monetised in an integrated capitals approach.

7.1 Conceptual framework – An Introduction to Economic Vulnerability of Natural and Human Capitals

This chapter offers a synthesis of approaches addressing economic damages after wildfires with particular emphasis on natural, human and manufactured assets and deals with the assessment of wildfire economic vulnerability under the perspective of *capitals approach*, a perspective applied to a broad set of assets (not only the reproducible one made by humans) that *considers the value of the impacts and dependencies on capital stocks (e.g., natural, human, social and produced/economic capital) to inform decision-making* (Capitals Coalition, 2021) (Figure 20).

Within this approach, three different strategies can be taken:

1. The analysis of each capital as a single unit.
2. The analysis of multiple capitals, showing the results for each capital 'side by side', and
3. The account of the inter-connections between all of them (*integrated capitals approach – ICA*).

The scope of this chapter is to propose examples from the literature and methods of valuation that refer to the economic analysis of single capitals and to provide the background necessary for the development of an integrated capitals approach for assessing wildfire damages.

The integration of the economic vulnerability with social and ecological dimension although only marginally proposed in the conclusions will be object of consideration in the Conclusions (Chapter 8).

The literature is rich of examples showing impacts of wildfires on several types of natural capital, such as forest, agricultural assets, and physical (manufactured) infrastructures, all having an important

[26] This chapter is based on the work and results achieved by the A1.2.4 working group and it is edited by the following authors of this deliverable: HUTTON (Simone Martino, Michaela Roberts, Tami Wooldridge, Maria Nijnik). Further contributors are Research Council of Spain (Paola Ovando, Bruno Moreira), University of Cordoba (Macarena Ortega, Juan Ramon Molina), ISIG (Ramona Velea, Riccardo Laterza, Olivia Ferrari), University of Rome 1 (Umberto Pernice, Giovanni Laneve), University of Alcala (Emilio Chuvieco, Fatima Arrogante, Clara Ochoa), IRD (Florent Mouillot).

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economic relevance to income generation. Although these elements represent an important component of the vulnerability, they are often considered independently or are partially integrated in wildfire vulnerability frameworks. Values like human life and health, affecting the human capital sphere are less considered, and even much less investigated are damages to social capital and social innovations in relations to wildfire risk reduction. The role played by social capital innovation, an essential element of an integrated capitals approach, is object of a detailed analysis in the chapter 4, and hence not considered in the following sections, although epidermically mentioned to stress the importance of moving towards an integrated analysis of societies affected by wildfires as proposed in the Figure 20.



Figure 21: The four capitals, Source: Scottish Government, 2022.

This chapter presents a non-systematic review of common (most important) assets impacted by wildfire (natural, human, and manufactured), and proposes in non-technical language an overview of methods used to assess a broad range of values at stake. Using the utilitarian framework adopted by economists, the chapter briefly introduces the methods required to assess market and non-market value of assets at risk. It focuses attention on the provisioning services of forest such as timber and non-timber forest products and regulating services such as carbon sequestration, soil erosion,

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recreation, and landscape amenity (to mention a few). Conversely, cultural services, with reference to relational values and sense of belonging to a place, a broad category that with difficulties can be measured within the pure economic value framework, are ignored in the analysis that is below proposed. Biodiversity has been investigated under two restrictive perspectives that are commonly targeted by the economic literature, the non-consumptive (use) values that recreational activities like wildlife watching generates, with consideration of charismatic species, and non-use preferences assigned to any living beings for their existence. In addition, methodologies for damages caused by fire on manufactured assets like properties and human assets such as health are described.

In the next sections it is before proposed the evidence of socio-economic vulnerabilities emerging from a recent literature. Values shown are explained by referring to the methodological approach based on linking the Total Economic Value with the "cascade" approach describing how from natural capital ecosystem services are generated. Then results present evidence on the economic impacts on natural capital, damages to economic activities and effects on manufactured and human health with a demonstration of potential damages at European territorial scale, focussing mainly on agricultural and forestry values, and ecosystem services provided by natures such as crop pollination, soil retention, flood control, carbon sequestration and water purification. Conclusions present some gaps and ideas of future development addressing the importance of tackling the wildfire vulnerability analysis by adopting an integrated capitals approach.

7.2 Methodology for Assessing Economic Impacts of Fire in FirEUrisk

This section describes the key searches of a recent literature reviewed to find evidence on the economic vulnerability of wildfires and then introduces the theoretical background and common methods adopted to assess economic damages caused by wildfires on several assets, with special focus on natural, human, and manufactured capitals. The methodological valuation introduces the Total Economic Value framework, the utilitarian framework used by mainstream economics to classify anthropocentric values, and then focuses on the concept of natural capital and the cascade of ecosystem services and benefits arising to humans. Emerging considerations are of relevance to better understand the results proposed in the section 7.3.

7.2.1 Literature Review

The literature review started with a preliminary analysis of 30 key papers selected by the authors on risk vulnerability and natural and socio-economic damage of wildfires. Further papers were found through search of the online database ISI Web of Science. Search strings used are reported in Table 9, but no protocol was published for the analysis of these searches (such as that proposed by ROSES, https://www.roses-reporting.com/, for systematic review reporting standard). To better characterise an integrated approach to the analysis of wildfire vulnerability, searches were extended to consider both the economic damage of wildfires to natural capital and socio-economic assets with the goal of exploring:

1. The impact that wildfires have on human capital – such as risk to health and lives.

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2. The contribution that social and human capitals can bring to mitigate wildfires such as training, participation in volunteer initiatives and information campaigns to reduce ignition and make humans less vulnerable to fire; and
3. The extent to which these themes are considered in wildfire vulnerability and risk framework.

Findings from these three points are essential to explore gaps that need to be addressed to build a more comprehensive wildfire vulnerability framework.

Table 9: List of search strings and results returned from ISI Web of Science considering as cut-off date of publications March 2022.

Search string	Papers found
"Forest fire" AND "economic impact assessment"	53
"Economic" AND "damage" AND" wildfire"	235
"Valuation" AND "damage" AND "wildfire"	27
"Valuation" AND "damage" AND "wildfire" AND Ecosystem services"	1
"Forest fire" AND "contingent valuation", OR "Willingness to pay" OR "WTP"; "forest fire" AND "choice experiment"; "forest fire" AND "hedonic price method" OR "HPM"; "forest fire" AND "travel cost"; "forest fire" AND "replacement cost"	40
"Forest fire" AND "built capital" OR "manufactured capital"; "forest fire" AND "capacity building"; forest fire" AND "financial capital"; "forest fire" AND "human capital"; forest fire" AND "social capital".	55

The full dataset of 411 documents was filtered based on the analysis of title, abstract, introduction and methods. Included papers are published in English and a limited number (only three) in Spanish and Portuguese. Inclusion criteria to retain papers in the dataset were the impacts of single and multiple fires on natural capital and human assets (in monetary and non-monetary units), as well as the analysis of vulnerability in wildfire risk framework. Other papers that were considered are those addressing the benefits of managing fires and dealing with resilience and adaptation to mitigate vulnerabilities. Papers that were not dealing clearly with these topics were excluded, as well as a few papers proposed in conference proceedings of difficult availability, including those published in Russian, Chinese and Korean.

Appendix B presents the papers selected reporting a broad range of monetary approaches (and a few papers addressing non-monetary valuation of environmental asset such as water and soil) to measure the broad set of capitals affected by wildfires. A synthesis on recurrent economic values is provided in the results and findings are used in the conclusions to formulate a preliminary idea of an integrated capitals approach to wildfire vulnerability.

7.2.1.1 Methodological framework and approaches for economic valuation: measuring ecosystem services, environmental externalities, and socio-economic values

This chapter describes how to assess monetary values of natural capital stock, goods, and ecosystem services. This is a brief overview that does not take into consideration some important critiques raised by scholars operating in the field of ecological economics such as the problem of incommensurability (i.e., having no common comparison), the implications of nature commodification, and the plurality

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of values (i.e., no one single correct value) (Chan et al., 2016; Diaz et al., 2018; Spash et al., 2022). This chapter refers mainly to instrumental or utilitarian values, which are related to the use of nature to improve human wellbeing, and intrinsic values which reflect the value that nature has (Turner et al., 2019). Notwithstanding this limitation, in the context of addressing wildfire vulnerability under different perspectives (social, economic, and ecological lenses) proposed by the different chapters of this report, the choice of addressing in this chapter instrumental values only, can contribute to navigate the reader to the comprehension of the motivations proposed by mainstream economics when valuing natural capital.

The anthropocentric or instrumental value is addressed by the well consolidated framework known as **Total Economic Value** (TEV) (Figure 21), consisting in the sum of use and non-use values. The use value refers to the benefits arising from a direct use of natural capital (e.g., timber and non-timber forest products) and indirect uses such as regulating services of climate, soil retention, soil fertility and water quality, to mention a few. The non-use value category is bounded by the existence value concept and encompasses intra generation altruism (i.e., wanting the asset/service to be maintained so others can use it), intergenerational altruism (*bequest value*, maintaining the service for future generation) and stewardship motivation (*existence value,* non-human resources generate benefits and/or interests simply knowing they exist, are as far as possible left undisturbed, etc., even if they are never utilised or experienced). (Pearce and Turner, 1989; Turner et al., 2019).

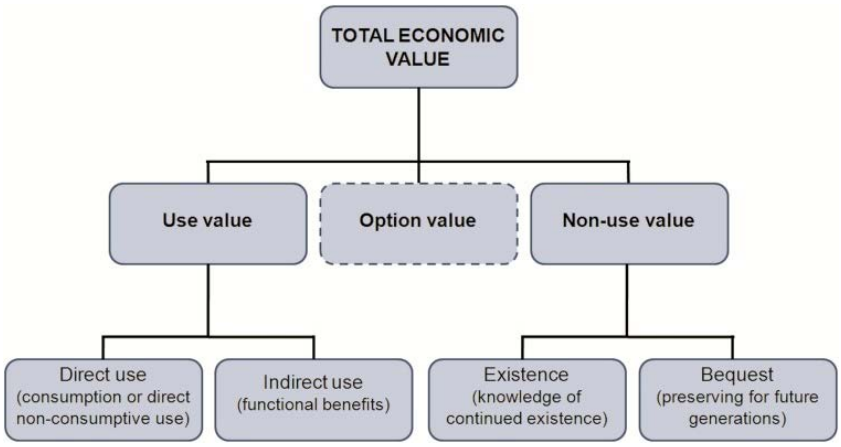


Figure 22: The total Economic Value (TEV) framework from the valuation of ecosystem services, source: Grant et al., 2013

Although the literature on values is recently proposing more complex frameworks to address value plurality (IPBES, 2022), the TEV is still a valid approach to address the instrumental values arising from the management of natural capital. The TEV can be applied to the final stage of the framework illustrated in Figure 20 that shows how natural capital, the stock of natural assets, such as air, water, soils, energy, etc., upon which humans depend, support natural processes such as primary productivity, water, and nutrient cycling, which in turn maintain those natural assets and support ecosystem functions. An ecosystem can be also considered a natural capital asset (UNSC, 2021) and all concepts of nature are reduced to capital in the economic terms, i.e., assets that contribute to the generation of wealth (Hache, 2019) according to capital theory developed by Hotelling (1931) and

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considered as pillar of The Ecosystem Accounting guidelines offered by the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA-EA), the new statistical standard adopted recently by the UN Statistical Commission (UNSC, 2021). Following this standard, three biophysical and two monetary accounts are suggested to be compiled:

1. ecosystem extent (size) accounts
2. ecosystem condition (quality) accounts
3. ecosystem services flow accounts in physical terms
4. ecosystem services flow accounts in monetary terms; and
5. monetary ecosystem asset accounts.

In this chapter it is addressed how to make an estimate of the main flows of goods and ecosystem services damaged by wildfires, as proposed by the account number (4), that underpin benefits to society, and in the demonstration section, it is proposed the monetary value of natural assets (account number 5) arising from the capitalization of the benefits generated by some ecosystem services over time.

The combination of stocks of natural capital and processes produces flows of ecosystem services as reported in Figure 22. These services have non-economic values in their own right (non-use values of biodiversity because of the right of the species to exist, etc.), but in many other cases their value or benefit to humans arises in combination with the services provided by other capital assets (such as human, social and manufactured, as proposed in Figure 23 – Costanza et al., 2014).

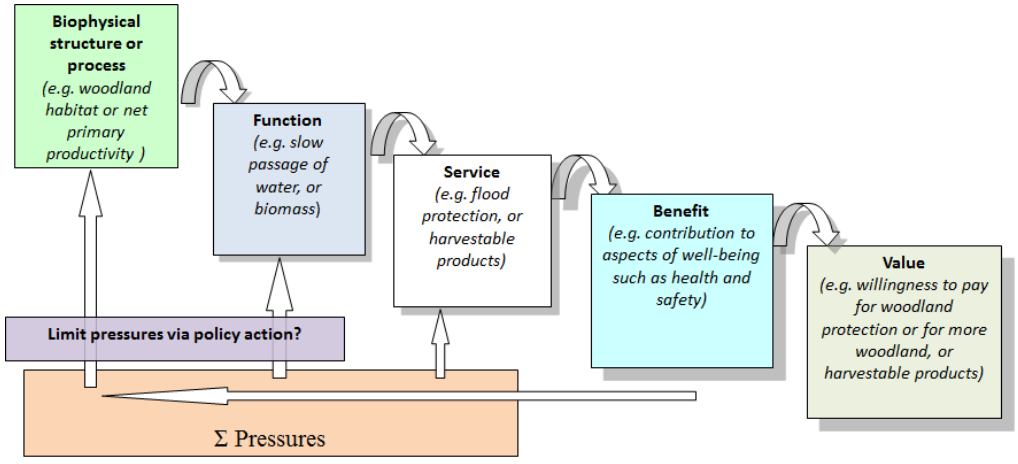


Figure 23: A cascade model of value generation from natural capital. Source: Potschin and HainesYoung, 2011.

The ecosystem services approach in Figure 21 is proposed as a linear cascade just for reasons of clarity. The complexities of biophysical functions depending on the conditions of habitats and the interactions between biotic and abiotic resources of the natural capital is indeed complex. However, the measurement of ecosystem services (goods and services that are generated by natural capital and that can be used by humans to enhance individual and societal wellbeing) is conceptually straightforward. From Figure 23 it is evident how wellbeing generation requires the combination of

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the ecosystem services flow with other forms of capital to produce wellbeing. For instance, the benefits and contribution to human wellbeing derived from forestry and agriculture ecosystem services require human labour, energy, machinery, and transport systems (Bateman and Mace, 2020) and cannot be produced directly by natural capital as depicted by the missing link between natural capital and human wellbeing ("*X*"), proposed in Figure 23. Moreover, some services provide many varied benefits. For example, biodiversity can be seen as a natural capital asset which provides services including maintaining ecosystem functions (Cardinale et al., 2012), enhancing productivity (Oliver et al, 2015), and providing recreational benefits (Hausman et al., 2016) or non-use values (Pascual et al., 2010). Thus, biodiversity can be included in ecosystem services assessments for underpinning ecosystem services or can be seen as a service. In this chapter, biodiversity is seen as a service per se, being assessed in the wildfire vulnerability literature as a recreational (wildlife watching) and non-use value (willingness to pay for existence of flagship species). For a list of ecosystem services addressed in this report we direct the reader to Table 10 proposed at the beginning of the results.

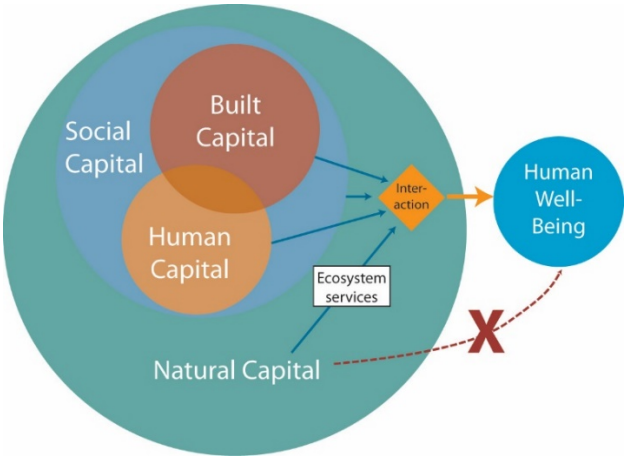


Figure 24: Framework illustrating the generation of benefits from natural capital; source: Costanza et al., 2014

When dealing with the impacts generated by wildfires on different set of capitals, complex interactions arise. In some cases, the relations between natural capital conditions and associated ecosystem functions depend not only upon ecological functions of the ecosystems but also upon anthropocentric drivers, such as pressure from land use, climate change and natural hazard (Bateman and Mace, 2020). For example, wildfires that alter ecosystem functions and generate a response from the ecosystem (resilience) can facilitate the transition towards a new equilibrium over space and time (Holling, 1973; Wu and Kim, 2013). Forest can be partially lost, and landscape transformed in grassland, reducing the ecosystems capacity of generating high value services (timber and carbon sequestration). In addition, the changes in natural capital extent and condition may generate reduction in landscape amenity and negative perception on recreational aspects of a burnt area (Molina et al., 2017).

To measure some of the most common values generated by natural capital and losses incurred after a wildfire, it is necessary to briefly introduce the methods to monetise assets or environmental goods from which people receive a benefit. To build a deeper knowledge on the methods proposed, it is

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recommended to read the methodology of the specific literature proposed in the results (see Appendix B for a full list). These methods are used to value damages caused by wildfires, classified in three categories according to Sangha et al. (2020):

1. Direct damages (to stocks) and (flows) of tangible assets (use values), mainly including public infrastructure, public, business, and private buildings, crop/farmland, forest, etc.
2. Non-marketable losses (indirect use values), or intangible losses that affect social (fatalities, injuries), psychological (health impacts), and environmental losses (externalities) such as carbon sequestration or other regulating ecosystem services provided by nature such as flood mitigation, water quality regulation, etc.
3. Indirect losses (use values) following the direct damages that cause business disruption, loss of public services including transportation, health, education, etc.

Results of this chapter present studies focussing particularly on damages mentioned in the first two points, while a general overview is dedicated to the analysis of indirect damages (point 3) according to the number of papers retrieved following the search strings proposed in Table 9.

7.2.2 Economic Approaches for the Evaluation of Marketed and Unpriced Environmental Goods

As proposed in the previous section, ecosystem services can provide a combination of goods and services. Benefits from ecosystem services can be valued through the market (i.e., formally traded) and non-market (i.e., limited, or non-traded) goods. Market goods can be easily valued through their market price (e.g., timber or food prices), however the value of non-market goods must be estimated indirectly. Because of the ease of valuation, market goods are more often included in analysis than non-market goods (Molina et al., 2014; Molina et al., 2018).

Market goods can be linked to unpriced environmental resources by the production function approach, a statistical method based on the construction of dose-response relation relevant to address the impact that natural capital may have on marketable outputs. Here the environment is treated as an "input" to the economic activity and its value is measured, like any other input, by the impact it has on the productivity of a marketed output. For example, Barbier et al. (2000) looked at the value of regulating ecosystem services like nursery and habitat functions of mangrove in supporting the fishing shrimp industry in south Thailand and Mexico. However, in the context of wildfire damages, this approach does not seem to be frequently adopted. An example is provided by Molina et al. (2011) who described how impact of wildfires to the Andalusian *dehesa* can be measured indirectly through the market value of swine feeding on *Quercus* species acorn. A possibility to explore this approach in the context of wildfire is to measure the change in values of agricultural products of soil after a burn due to the expected loss of fertility (Rodriguez y Silva, 2013). Hedonic functions, as before mentioned, are more commonly used to investigate the impact that wildfires have on the value of property (Kiel and Matheson, 2018) (see section on manufactured capital).

If these goods contribute to human wellbeing, they still have economic value, even without a market price (Bateman et al., 2002), that can emerge recurring to a broad range of approaches based on the analysis of individuals' preferences elicited by using either stated or revealed approaches (Turner et

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al. 2003). Stated preferences approaches (e.g., contingent valuation method (CVM) - Hanemann, 1994) and choice experiments (CE) (Birol et al., 2006), elicit respondents' preferences in hypothetical scenarios, and are the only ones considered to effectively deal with non-use values (Arrow et al., 1993). Respondents are asked either for their willingness to pay (WTP) for protection or enhancement of the environmental good of interest, or (less commonly) their willingness to accept (WTA) for accepting its loss. In CVM, people are asked to directly state their WTP or WTA in relation to a clearly described single environmental or policy change, for instance for the conservation of charismatic species (Saayman & Saayman 2017; Cazabon-Mannette et al. 2017), while in CE, respondents are asked to consider several alternatives, described on the basis of multiple environmental or policy changes (attributes) of the asset at stake, typically with a monetary cost attached to them and with a status quo at no cost (add reference here). To hypothetically value the different attributes by contingent valuation, a series of contingent valuation studies would have to be designed for each attribute separately, which is very resource intensive (Bateman et al., 2002; Bennett and Adamowicz, 2001).

Conventionally, stated preference methods are conducted via questionnaires, but there is increasing interest in deliberative monetary valuation (DMV) approaches where people state their values after group discussions (Bunse et al., 2015). We have not found any implementation of DMV to the valuation of wildfire damages and risk analysis.

Differently from stated preferences, revealed preferences approaches use observed market data on priced commodity to infer preferences for marginal changes in the quality or quantity of an environmental good associated with the marketed good (Bockstael & McConnell, 1993). Information from markets is used to infer a value and a private good qualifies as a proxy if it is consumed as a precondition for benefitting from the public good that is the object of valuation. Two key approaches include the hedonic pricing method (HPM) and travel cost method (TCM). By employing HPM the value of the environmental goods (e.g., the value of landscape amenity) is measured as marginal impact on the value of immobile assets, typically premises or land (González-Cabán et al., 2007), by employing regression analysis. Under the TCM, preferences are revealed from money spent in travelling and the number of visits to a certain area to derive the economic value of the recreational experience (Perman et al., 2003; Tol., 2014).

Finally, approaches based on cost, such as avoided damage-cost, and replacement cost can also be used for wildlife valuation. In the former, the benefits that are valued are considered at least equal to the avoided damages; for example, where natural predators control pests, the value of the predator is equal to the damage caused by the pests if left uncontrolled. In the latter, minimum values of environmental goods are equated with the cost of replacing them by human solutions. For example, the cost of hiring honey beehives is a proxy for the value of the services provided by wild pollinators (Sandhu et al., 2008; 2015). An example of cost method valuation applied to wildfire vulnerability is proposed by Oehler et al (2012) who reconstructed the cost of different land cover types in the entire European territory according to the intensity of fire. This approach has been recently adopted for the risk management strategy proposed by JRC in the Pan-European wildfire risk assessment (Jacome Felix Oom et al., 2022).

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7.3 Results of Economic Impact Assessment of Fires in FirEUrisk

This section provides a synthesis of the findings of the literature review emphasising the different aspects related to the analysis of capitals affected by wildfires. After a classification of the main topics proposed by the literature, we analyse the most common damages to natural and human and manufactured capitals that can be relevantly assessed using a monetary valuation approach. Each of these capitals will be object of a single section.

7.3.1 Classification of the Papers Reviewed

Reviewed papers were classified in three groups: "Non-economic impacts on Natural Capital", "Natural Capital and ecosystem services valuation and socio-economic impacts", and "Risk Analysis and Vulnerability". Focus here is mainly on the first two groups; the first group is relevant to build the knowledge to marginally tackle ecological values; while the second group to address more deeply ecosystem services and socio-economic activities affected by wildfires.

Within the first group of studies a preeminent role was played by papers addressing damages and disturbances to forest ecosystem dynamics (Wu & Kim, 2013; Aleksić et al., 2009), changes to dominant vegetation and biodiversity (Adams, 2013), and indirect shifts caused by grass invasion (Morais et al., 2021; Kerns et al., 2020). Higher impacts of pests and diseases on plant survival, variations in traits expression (Lerch et al. 2016; Bélanger et al., 2013; Salazar et al., 2020), and reduction in forest resilience (Wu & Kim, 2013) were also commonly studied. Less investigated are impacts on water quality and soils retention although some evidence is emerging (Montagné-Huck & Brunette, 2018; Parise & Cannon, 2017; Sarro et al., 2021; Certini, 2005). As regards the second group of studies (Natural Capital and ecosystem services valuation and socio-economic impacts), many papers focused on assessing the socio-economic impacts of wildfires on agriculture and agroforestry system by using market approaches (Molina et al., 2011; Stougiannidou et al., 2020; Fagarazzi et al., 2021). Also, research addressed multiple forest ecosystem services, including timber, carbon and biodiversity (Aleksić et al., 2009; Mueller et al., 2019; Varela et al., 2016), landscape amenities and recreational values (Molina, Rodríguez y Silva F., 2019; Molina et al., 2018) by employing a mix of stated (contingent valuation and choice experiments) and revealed preference approaches (travel cost method). A high number of papers addressed damages to health such as respiratory morbidity and cardiovascular diseases caused by haze smoke pollutant and contamination rates (Liu et al., 2015), or other physical consequences such as reduced height in adult age (Rosales-Rueda & Triyana, 2018; Sing & Dey, 2021). However, economic estimates remain sparce, focussing on cost of medical treatment and hospital admittance (Stanke et al., 2013), willingness to pay for avoiding respiratory disease (Jones, 2018; Leslie et al., 2013) and mitigating smoke exposure (Haider et al., 2019). In addition to the impacts on natural capital and economic assets, the literature has focused on the interactions between wildfires and social relations. This is only marginally considered here just to provide the reader with an idea of the arguments proposed by the literature, but not addressed because this is the subject of chapter 4. A limited number of studies provide evidence of fire as a lever to increase management actions that reduce wildfire risk by promoting community engagement, training and discussions. Examples from the Global South, in countries like Nepal, India, Seychelles and Indonesia, as those promoted by Hiratsuka et al. (2019), Chauhan et al. (2021), Etongo et al. (2021), respectively, and in Western nations, are found to build a stronger nexus between policy makers and scientists

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(Narayanan et al., 2009; Tabara et al., 2003; Huber-Stearns et al., 2021) by the integration of spatial data and models of wildfire behaviour in decision making. Relevant is the contribution that the impact of wildfires has on strengthening communities with local institutions such as municipalities and fire fighters as evidenced in Australia (Mc Dougall et al., 2014) and in countries like Nepal and Indonesia, where collective actions were able to enforce rules for risk mitigation (Sapkota et al., 2015; Jalil et al., 2021). In Mediterranean countries voluntary initiatives at local levels and structural and relational bonding between communities and institutions are found to statistically explain the community's operational capacity and perception of arson level (Górriz-Mifsud et al., 2019).

A list of capitals, values, and methods proposed by key papers found in the literature are reported in the Table 10. These values will be described in more detail in the next sections.

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Table 10: Indicators and proxies of different capitals that are commonly investigated in the wildfire context.

Capital	Indicator	Proxy	Method	Unit of measure	reference
Natural capital	Carbon sequestration	Carbon sequestered	Social cost of carbon/ carbon market price	Physical units and monetary	Valatin (2014); Molina, Herrera, Rodriguez y Silva (2019)
	Timber	Timber volume marketed	Market price	Physical units and monetary	Sil et al. (2019)
	Non timber forest product	Mushrooms and firewood volume marketed	Market price	Physical units and monetary	Sil et al. (2019)
	Biodiversity	flagship species	Public investment; contingent valuation method	Monetary	Molina, Zamora, Rodriguez (2019)
	Biodiversity-	flagship species	Choice experiment	Time to voluntary activities to reduce wildfires ad biodiversity loss	Durán-Medraño et al. (2017)
	landscape	Fire regulation capacity	Market price of provisioning services	Monetary	Sil et al. (2019);
	Landscape	landscape quality	Contingent rating	Monetary	Molina et al. (2016)
	Landscape	Landscape resilience to wildfires intensity	Net value change	Monetary	Thompson et al., (2011)
	Landscape	Landscape value by analysis of preferences and landscape economic losses in terms of visit among fire intensity levels	Contingent valuation method + Net value change	Monetary	Molina et al. (2018)

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	Landscape	Potential landscape damage caused by fire under fire probabilistic risk	Contingent valuation +GIS analysis for landscape quality analysis and burn probability	Monetary	Molina et al. (2017)
	Recreation	Number and cost of trips to areas with burn history	Travel cost method	Monetary	Boxall and Englin (2018); Molina, González-Cabán and Rodríguez y Silva, (2019)
	Recreation	expected changes in number under different by fire scenarios for hikers, bikers, users of rivers and for the entire national park	Travel cost + stated preference (CVM)	Monetary	Loomis, Gonzalez-Caban and Englin (2001) Sánchez, Baerenklau and González-Cabán (2016); Boxall and Englin, (2018); Molina, González-Cabán and Rodríguez y Silva (2019)
	Multiple services	ecosystem restoration of a watershed – analysis of cultural ecosystem services, such as public access to the watershed area and areas of cultural significance for native Americans	Choice experiment	Monetary	Mueller et al. (2019)

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	Multiple services	carbon sequestration; number of tree species, as a proxy of biodiversity, the share of pine forest area suitable for recreation, and the annual burned areas due to forest fires	Choice experiment	Monetary	Varela et al. (2017)
Natural capital/Socio-economic value	Agricultural values	Yearly and permanent crops (fruit trees, olive trees, etc.) and cost of reconstruction and rehabilitation	Market price	Monetary	Brémond et al. (2013); Stougiannidou et al., (2020) – See Appendix II for values estimated at European Scale NUTS2
Socio-economic damage	Macroeconomic damage	Employment	Econometric analysis	Monetary and units of employment	Moseley and Gebert (2014)
	Macroeconomic damage	Impacts on economy of a country - Values at stake are damaged capital, the health costs related to air pollution exposure, and indirect losses due to broader economic disruption cascading along with regional and national supply chains	modelling approach building on physical, epidemiological, and economic models -	Monetary	Wang et al. (2021)
Human capital	Life	Life	contingent valuation methods- willingness-to-accept	Monetary	Jones-Lee & Loomes (1997)

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			compensation for incurring a risk		
	Health	Respiratory disease	Contingent valuation method - willingness to pay for avoiding respiratory disease	Monetary	Jones (2018); Leslie et al. (2013); Richardson et al. (2013)
	Health	Respiratory disease	COI (cost of illness) - cost of medical treatment and hospital admittance	Monetary	Stanke et al. (2013); Richardson et al. (2013)
	Health	Respiratory disease	revealing the behaviour of people in taking action to reduce illness	Monetary	Richardson et al., (2012); Richardson et al. (2013)
	Health	wildfire smoke health cost	benefit transfer approach – based on wildfire dose response function	Monetary	Jones et al. (2016)
	Health	effect of wildfire smoke on health outcomes and further the effect of such health outcome changes on life satisfaction	Life satisfaction approach	Monetary	Jones (2018)
	Health	Comparison between economic benefits of avoiding health damages from haze from forest fires outweigh the economic costs of alternative policies	Cost benefit analysis	Monetary	Tan Soo & Pattanayak (2019)

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Manufactured capital	Built infrastructure	Houses/properties	Market price	Monetary	Roman et al. (2013)
	Built infrastructure	Houses/properties - housing price data is used to estimate implicit prices of environmental hazards (wildfire)	Hedonic price method	Monetary	Stetler et al. (2010); Mueller & Loomis (2014)
	Built infrastructure	Houses/properties - use housing price data is used estimate implicit prices of environmental hazards (wildfire) along with risk perception	Hedonic price method	Monetary	Kiel and Matheson (2018)

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7.3.2 Analysis of Natural Capital in the Context of Wildfire Vulnerability

This section reviews some economic studies dealing with wildfire impacts on natural capital and in particular the ecosystem services flow accounts in physical and monetary terms as proposed by the UN SEEA-EA (UNCS, 2021), but does not consider aspects of natural capital affected by fire that are not object of monetary valuation and that can be considered *ecological values* formulated as "wildness" of biota, protected areas and forest biomass, just to mention a few common proxies. Such values can also include water and soil quality and soil organic carbon. Reader can refer to chapter 6 for the approach proposed for the analysis of ecological values.

Biodiversity deserves a separate consideration. Under the natural capital approach biodiversity is not considered a natural asset, but a condition that enables the natural capital to generate ecosystem services (Capitals Coalition and Cambridge Conservation Initiative, 2020). In this chapter, biodiversity is considered as a final good generating both use and non-use values. Utilitarian values of biodiversity (e.g., recreational values) as well as intrinsic values as existence of certain species have been elicited in the literature (e.g., Huang et al., 2013; Molina, Herrera, Rodriguez y Silva, 2019; Molina, Rodriguez y Silva, Ruiz, 2019) and proposed in the following sections.

Diverse aspects of natural capital valuation related to ecosystem services, targeting provisioning, regulating and cultural values affected by wildfires are proposed. As regards provisioning ecosystem services, consideration is given to timber and non-timber forest products (e.g., mushrooms, firewoods). Among the regulating services, focus is on carbon sequestration, and for the most common cultural values, recreational values and landscape amenities are considered. Values proposed in the selected literature are welfare measures or utility provided to consumers by a marginal or incremental change of the goods/services at stake (Dasgupta, 2021) using the approaches proposed in the methodological section. A summary of the values estimated for the natural capital assets is provided in the Table 11 at the end of this section.

7.3.2.1 Ecosystem services provided by forests

The effect of wildfires on ecosystem services (ES) has been addressed at different spatial scales, including the landscape level (e.g., Huang et al., 2013; Molina, Herrera, Rodriguez y Silva, 2019; Sil et al., 2019), watersheds (e.g., Mueller et al., 2019) or even regions (e.g., Varela et al., 2017). Research applies diverse methods and approaches to the economic interactions between wildfires and natural capital values. Some studies offer estimates of economic benefits of reducing wildfires frequency or their intensity on the basis of the economic values associated to the provision of ecosystem services (e.g., Huang et al., 2013; Molina, Herrera, Rodriguez y Silva, 2019; Sil et al., 2019) or avoiding damages to natural capital and biodiversity (e.g., Huang et al., 2013; Durán-Medraño et al., 2017; Molina, Rodriguez y Silva, Ruiz, 2019). Others analyse social benefits or social demand for forest conservation or management practices, which rather treat the reduction in forest fires incidence or the enhancement of the ecosystem resilience to wildfires as attributes of these forestry alternatives (Varela et al., 2017). The next subsections discuss the approaches used by the referred studies to estimate the economic effect of wildfires on natural capital values, with focus on carbon flows and stocks, biodiversity, provisioning services and the multiple ES approaches.

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7.3.2.1.1 Carbon sequestration values

Disturbances such as wildfires are important source of greenhouse gas (GHG) emissions from biomass burning and soil C stock losses; it can take years to decades to recover pre-disturbance soil and vegetation C stock levels (Mayer et al., 2020). Typically, carbon losses due to environmental disturbances or management are estimated in physical terms and priced considering either social or market values (Valatin, 2014). There are different ways to measure the value of carbon. The "social cost of carbon" is typically referred to the *marginal cost of damaged produced* by an extra tonne of carbon dioxide that is released to the atmosphere, but it can also be referred to the *marginal GHG abatement costs* required to meet a given climate stabilisation goal. Whilst the *market prices* of carbon refer to those observed in compliance and/or voluntary carbon markets.

What is a substantial concern in the valuation of carbon storage and sequestration is the wide range of carbon prices, ranging from few dollars to over hundreds of dollars per tonne, and the lack of internationally agreed methodology for estimating the social value of carbon, with existing prices reflecting mainly national conventions (Valatin, 2014). This variability is also highly important regarding the physical accounting of forest carbon losses, in particular concerning impacts of fire on soil carbon dynamics (Mayer et al., 2020). A full economic valuation of the impact of wildfires on forest carbon stocks would ideally account for the carbon stored in plants biomass and soil, and carbon recovery dynamics balance. The latter is usually omitted in the papers found in the literature.

Molina, Herrera, Rodriguez y Silva (2019) for example estimate the potential economic losses associated to forest carbon, considering both carbon stock and the discounted expected carbon sequestration until the forest rotation age is reached, in view of the age of the stand the moment the fire occurred. For estimating carbon stock these authors use a combination of methods, including destructive sampling to quantify dry biomass and carbon and allometric functions to estimate carbon storage in above and below ground (alive and dead) biomass of trees and shrubs. The potential impact of wildfires on carbon stock is then modelled spatially considering differences in tree canopy and shrub strata according to a field forest inventory, and scenarios of fire intensity. Molina, Herrera and Rodriguez y Silva (2019) use average international carbon market prices (based on the EU Emission Trading System compliance market)[27] to value the potential carbon losses, apparently considering the specific date a wildfire occurred.

A carbon accounting approach is also used to estimate avoided GHG emissions as result, for example, of treatments to reduce wildfire risk in *Ponderosa pine* forest, Oregon, USA (Huang et al. 2013). First these authors estimate the effect of the level of fuel reduction treatments on the project reversal risk rating under the Climate Action Reserve (CAR) forest projects protocol[28]. The CAR risk rating

[27] Authors refer to the SendeCO2 which is a webpage that records daily CO_2 prices observed in the EU ETS since it was launched in 2008. The EU ETS is a cap-and-trade scheme to reduce GHG emissions, whereas land use carbon credits are not eligible, thought it can only operate as a proxy market.

[28] CAR protocols were developed under the Verified Carbon Standard (VCS) program, which is the most widely used voluntary GHG program. This program has been widely used to validate and verify forest carbon offsets,

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determines the project´s annual contribution to a carbon buffered pool (C reserve tonnes) which cannot be issued in a carbon offsetting market. Second, Huang et al. (2013) quantify the carbon stock balance with and without the treatment including above and below ground carbon in standing dead and alive trees, carbon in woody debris or litter, and C releases from wildfires for the scenarios considered. Carbon benefits are then valued using a marginal cost of GHG abatement in the US, while costs are related to the application of the treatments[29].

7.3.2.1.2 Biodiversity values

Biodiversity directly contributes to human health, it can be source of enjoyment, and has a key role in making available a wide range of goods and services on which societies depend. People also ascribe a value to the existence of specific species even if there is no direct experience. Furthermore, some also argue that biodiversity has an intrinsic value independent of whether it means something to people, for example in connection to its moral worth (Dasgupta, 2021). Typically, economists have addressed biodiversity valuation with focus on specific species, in particular the endangered ones or flagship species. This is also the situation for the few studies found in the literature embarking upon the economic valuation of wildfires effect on biodiversity. For example, Molina, Zamora and Rodriguez y Silva (2019) apply two different (but complementary) approaches to estimate the value of flagship species, and on this basis, they estimate both direct and indirect impacts of wildfires on biodiversity. These authors assess, on one hand, the recovery cost of flagship species populations (and their habitats) analysing public investment in recovery programs in the study case areas over the past decades. And on the other hand, they conduct a contingent valuation (CV) survey to elicit people's willingness to pay (WTP), in form of a monetary annual donation, for the conservation of a selection of flagship species of different IUCN´s conservation levels[30]. The asset value of a particular flagship species is estimated by capitalizing the discounted value of: (i) its specific average annual public expenditure over the time needed to recover the species habitats (i.e., recovery of food and shelter), or alternatively (ii) the annual mean WTP of Andalusian people for the conservation of an individual of a particular flagship species. For the estimation of the impact of wildfires on biodiversity, Molina, Zamora, Rodriguez y Silva (2019) ascribe the full flagship species asset value to dead individuals (those that could not escape the flames or smog during the wildfire event), and a partial value (a percentage) reliant on the population decrease in the burnt areas due to migration to other areas.

for which CAR protocols set the criteria to estimate the contribution of the project to the pooled carbon buffer account to respond to the project-specific carbon non-permanence and leakage risks, including wildfires and other factors. The pooled buffer account is a reserve of non-tradable carbon credits that serves as a shared insurance pool for all VCS project involving agriculture, forestry and other land use (VERRA, 2013).

[29] Avoided GHG emission in Huang et al. (2013) paper are one of the expected benefits of fuel treatment measured as the avoided costs from wildfires. These estimated avoided costs also include avoided: (i) fatalities, (ii) timber losses, (iii) fire suppression costs, (iv) facility (property), and (v) recovery costs from forest ecosystems restoration.

[30] Relatively little information about the survey is provided and the target population does not seem representative. The survey was conducted in a university workshop with 231 responses.

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Discrete Choice experiment (DCE) has also been used to estimate people's WTP for improving or changing environmental conditions (e.g., reducing the incidence or intensity of wildfires). Durán-Medraño et al. (2017) led a DCE with a sample of Social Sciences University Students[31] in Galicia (North of Spain) to measure their willingness to devote, on a voluntary basis, working days to carry out forest wildfire prevention activities (e.g., shrubs clearing, pruning), giving up part of their leisure time in Spring[32]. In addition, participants were asked to whether they would work four paid hours on top to the voluntary ones, and if so, what would be the minimum salary to do that, to have some monetary approximation to the value of the voluntary work. The wildfire prevention management program proposed to the participants aims to reduce the impacts of forest fires (making them less severe) in coastal areas, and thereby reduce biodiversity losses on different ecosystems.

7.3.2.1.3 Provisioning services of forest ecosystems

Sil et al. (2019) analyse the effect on farmland abandonment in mountain landscapes of Northern Portugal on the fire regulation capacity of ecosystems and assess the economic value of the loss of this function on the basis of the impact of fires in the supply and market prices of three provisioning ES. Those services include timber (softwood), firewood and wild mushrooms. The tree ecosystem services are valued considering average market prices for these goods reported in the study site area, while their biophysical quantities are estimated based on local-based data and models. Landscape fires regulation capacity is estimated considering fire intensity and burnt areas observed between 1990 and 2006 in the area, and three alternative management scenarios to explore different pathways of landscape evolution, and its effect on fire regulation capacity[33].

7.3.2.1.4 Multiple-ecosystem services valuation

Reducing the intensity and risk of wildfires is expected to avoid losses of multiple benefits from forest that are relevant for society (Costanza et al. 2014; Campos et al., 2019). Two studies found in the specialised literature, Mueller et al. (2019) and Varela et al. (2017), value multiple benefits, including ecosystem services, of forest management aimed at reducing threats to ecosystems conservations, including wildfires. Mueller et al. (2019) conduct a DCE to elicit public support and preferences concerning ecosystem restoration of a watershed that provides ES to the metropolitan Phoenix (US) area (549 responses). The attributes considered in this experiment include cultural ecosystem services, such as public access to the watershed area and areas of cultural significance for native Americans, and regulating services such as ground water recharge, surface water quality regulation and maintaining critical habitats. The payment vehicle was defined by a one-time fee that would be

[31] 240 students were interviewed. The population is not representative of Galician population, therefore any extrapolation of these data to the regional population is not consistent.

[32] For adding credibility to the payment vehicle (and avoiding the hypothetical bias) participants were asked to fill a planning calendar with their time availability and provide an email address to be contacted and enrolled by a trust agency.

[33] Sil et al. (2019) apply a spatial explicit process-based model that uses information on land cover, weather, and topography to simulate fire propagation and intensity, which is applied to simulate the effect of 1996 and 2006 fires and the 2020 land abandonment/management scenarios.

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used solely for the watershed case study. Restriction of public access, which is an attribute in the DCE, is nonetheless presented as a measure to reduce the risk of human-caused wildfires. The results of Mueller et al. (2019) suggest that respondents are willing to postpone current public access to recreation to reduce this wildfire risk and with it ensure long-term forest health.

Varela et al. (2017) also apply a choice experiment to elicit people jointly preference for a set of attributes, which are referred to as 'externalities', derived from current and enhanced forest management practices in a pine forest in Catalonia, Spain. In this case the attributes analysed are not strictly ecosystem services, except for the carbon sequestration[34]. Those rather indicate some characteristics of the forest management alternatives that would influence the provision of ES. Those additional attributes include the number of tree species, as a proxy of biodiversity, the share of pine forest area suitable for recreation, and the annual burned areas due to forest fires. The payment vehicle is an annual increase in regional taxes and the DCE is conducted with a representative sample of the Catalonia population (410 responses).

[34] Carbon sequestration is expressed in terms of the Catalonia population emissions that would be offset by the forest enhanced management project.

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Table 11: List of monetary values at stake for natural capital affected by wildfires.

Author	Value at stake	Valuation method	Geographic area	Monetary value	Unit	Year of the study
Durán-Medraño et al., 2017	Biodiversity (voluntary actions to reduce wildfires to avoid biodiversity losses and displacement of local wildlife)	Discrete Choice Experiment (WTP to devote, on a voluntary basis, working days to carry out forest wildfire prevention activities)	Galicia (Spain)	132.26-166.73	€/person	October 2013-March 2014
Huang et al., 2013	Carbon (effect of forest treatment on carbon stock balance and the carbon units to be issued in offsetting markets, through reserving carbon loss risk)	[marginal] Abatement (applied to estimated carbon credits for the treatment alternatives)	Oregon (US)	2.65- 404.65	US $/ha	Prices referred to an US EPA document of 2009
Molina, Herrera & Rodríguez y Silva, 2019	Carbon (economic value of fire impacts on carbon storage)	Scenario analysis of fire impacts on carbon stock values per type of land use Single average prices (based on EU ETS)	Two sites (Vértice and Catena) affected by fires in Andalusia (Spain)	Vértice: 54.64-811.79 Catena: 1,375.94-12,398.68	€/ha	2008-2018 (prices from the EU ETS)
Molina, Zamora & Rodríguez y Silva., 2019b	Biodiversity (flagship species asset value applied to estimate biodiversity loses from dead individuals in a wildfire event, and decrease in population due to migration to other areas)	1) Recovery cost (based on public investment in recovery programs over the last 12 years)	Two protected areas (Doñaña and Segura) affected by fires in Andalusia (Spain)	Doñaña 1) 74.89-81.70 2) 105.7-115.3 Segura 1) 0.76-0.94 2) 3.75-3.92	€/ha total wildfire impact	Not clear (WTP referred to a study published in 2016)

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Author	Value at stake	Valuation method	Geographic area	Monetary value	Unit	Year of the study
		2) Contingent valuation				
Mueller et al., 2019	Multiple ecosystem services approach (public access to the watershed area and areas cultural significance for native Americans, ground water recharge, surface water quality regulation and maintaining critical habitats)	Choice Experiment (WTP for watershed restoration considering ES provision levels as attributes), and connect public access restriction to reduce risks of human caused wildfires	Salt Verde River watershed providing services to Metropolitan Phoenix (US)	25.81 (for restricting access during the wildfire season) (41.92 for restoring critical habitats 40.19 for improving surface water)	US $/person	2016 (apparently)
Sil et al., 2019	Provisioning services (cultivated biomass: timber, firewood and wild biomass: mushrooms)	Market valuation (prices reported in the study area) of income losses due to wildfires	Upper basin of the Sabor river (Portugal)	-1,021 -2,222 -3,038	€/ha	1990 2006 2020
Varela et al., 2017	Multiple benefits from enhancing forest management practices (increasing carbon sequestration, biodiversity through diversification of forests, increasing the land available for recreation and reducing burnt areas)	Choice experiment (estimate social preferences (WTP) for environmental externalities, including a scenario that reduces the burned area)	Aleppo pine forest in Catalonia (Spain)	2,044.23	€/ha	Between August and September 2011

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7.3.3 Recreation Valuation and Impacts Caused by Wildfires

Forest areas are popular for recreation, relating often to the landscape and nature connection as well as provided amenities such as biking trails and support services (Boxall and Englin, 2018). Because most of the forest recreation does not have a market value, non-market techniques are most often used to value the changes to recreation caused by fire, or fire management. This lack of market value can also mean that recreation impacts of fire and its management are often overlooked in cost benefit analysis of fire management planning (Boxall and Englin, 2018; Molina, González-Cabán and Rodríguez y Silva, 2019). Recreation values of forest fires, or forest fire management, are estimated using travel cost models (TCM) linked to stated preferences (Perman et al. 2003). Table 12 shows some estimates of recent studied conducted in the US and Europe.

Studies have included comparing numbers and costs of trips to areas with different burn histories (Loomis, Gonzalez-Caban and Englin, 2001; Hesseln et al., 2003; Hesseln, Loomis and González-Cabán, 2004; Boxall and Englin, 2018; Molina, González-Cabán and Rodríguez y Silva, 2019), with one study considering only trips to unburned areas (Sánchez, Baerenklau and González-Cabán, 2016). To further explore the differences in preferences each study also included a stated preference section, exploring how trips may change in either frequency or location based on alternative fire scenarios. Values were then estimated either over hiking and biking (Loomis, Gonzalez-Caban and Englin, 2001; Hesseln et al., 2003; Hesseln, Loomis and González-Cabán, 2004; Sánchez, Baerenklau and González-Cabán, 2016) or river routes (Boxall and Englin, 2018), or estimated across a National Park (Molina, González-Cabán and Rodríguez y Silva, 2019).

Impacts of fire on recreation values for hikers and mountain bikers in National Forests in Colorado (Loomis, Gonzalez-Caban and Englin, 2001), New Mexico (Hesseln et al., 2003) and Montana (Hesseln, Loomis and González-Cabán, 2004) were all studied using identical methods. Visitors were asked about trails visited and total travel costs, including costs of staying in the area. The revealed preferences were integrated with a contingent valuation question as to whether the trip would still have been taken at an additional cost, ranging from $3 to $70, and whether the trip would have taken place under three alternative fire scenarios: 1) Half trail experienced high intensity crown fire; 2) Half trail experienced light prescribed burn; 3) Half trail experienced high intensity fire 20 years ago.

In all studies hikers and bikers showed preferences for areas that had not undergone the high intensity crown fires. In areas which had undergone high intensity burning, hikers had a higher preference for recently burned sites, declining as the time since the fire increased, likely linked to the novelty of wildflowers in newly burned areas. Bikers did not show this preference, preferring areas with longer time since high intensity fire (Loomis, Gonzalez-Caban and Englin, 2001; Hesseln et al., 2003; Hesseln, Loomis and González-Cabán, 2004). Only one study detailed valuation in Europe, estimating the value of forest in a National Park in Spain. Unlike other studies, this study estimates value across the whole park, taking a zonal method to estimate values for potential users. Visitors to the park identified the full costs of their visits, including travel, accommodation, and subsistence, and then carried out a contingent valuation study as to how number of visits would change as a result of changes to the landscape caused by fire. GIS data was used to understand vegetation composition of the park, and therefore predict fire behaviour and vegetation resiliency to fire. Using values estimated by the travel cost and contingent valuation study, and stratified by population within each zonal distance band, the

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total economic susceptibility of the park, accounting for fire behaviour and vegetation resiliency, was estimated between €31-89 million (Molina, González-Cabán and Rodríguez y Silva, 2019).

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Table 12: List of monetary values at stake for recreational values affected by wildfires.

Author	Value at stake	Valuation method	Geographic area	Monetary value	Unit	Year of the study
Boxall and Englin 2008	Recreation (river sport)	Travel cost and contingent valuation	Nopiming Provincial Park, Canada	Increased value of route immediately following fire (1-year), declining at 10 years post burn, and then increasing again 35 years post burn	$/trip	1995
Loomis et al 2001	Recreation (hiking and biking)	Travel cost and contingent valuation	Colorado national forests	Bikers – Trip increase from 1.29 to 3 between 0 to 40 years post crown fire. Value increase $62 - $138. No change for non-crown fire. Hikers – trip decrease from 3.03 to 2.78 0 to 40 years post crown fire, and value from $145 to $55. Non-crown fire trips increase 2.65-3.97, but value decrease $34-$24	Number of trips $/trip	1998
Hesseln et al 2004	Recreation (hiking and biking)	Travel cost	Montana national forests	No change in trip frequency for hikers or bikers	Number of trips	2000
Sanchez et al 2016	Recreation (hiking)	Travel cost and choice experiment	San Jacinto Wilderness Area, California	Welfare gain for hikers for 25% of trail burned mean of $106.35.	$/trip	2012

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				Loss of sites access due to fire welfare loss of $23.92 to $164.05, with loss of all sites at $281.23		
Molina et al 2019	Recreation (hiking)	Travel cost	Sierra de Aracena y Picos de Aroches Natural Park, Spain	Potential loss to park based on recreation value and vegetation resilience estimated at between 31,210,807 and 89,460,204 Euro	Euro	Unclear
Hesseln et al 2003	Recreation (hiking and biking)	Travel cost and contingent valuation	New Mexico national forests	Bikers – Trip decrease from 0.02 to 0 between 0 to 40 years post crown fire. Value decrease $9.66 - $7.19. For non-crown fire trips decrease from 6.91 to 0.73, and value from $150.53 to $25.80 Hikers – trip decrease from 1.24 to 0.95 0 to 40 years post crown fire, and value increase from $90.92 to $107.35. Non-crown fire trips decrease 1.93-0.06, and value decrease $130.24-$51.87	Number of trips $/trip	2001

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7.3.3.1 Wildfire impacts on landscape resources

Although low-intensity fires could have positive effects on fire-prone ecosystems, fire impacts on a landscape level are viewed as negative changes in quality and socioeconomic value of the natural resources. A comprehensive valuation including the value of landscape should be considered to complement the value of those ecosystem services depicted in the previous sections (de Groot et al., 2010). However, environmental and landscape services are rarely incorporated into economic valuation of natural resources, even though these resources may constitute a large proportion of the total ecosystem value. For instance, in Portugal, the value of ecosystem services including landscape ranged from € 1,021/ha (rural abandonment) to € 3,430/ha (forest expansion) (Sil et al., 2019).

One of the most difficult things to do in valuing the economic impact of fire on natural resources is to determine the economic value lost. Damages can be quantified using the net value change approach (NVC), a function of landscape resilience and fire intensity (Thompson et al., 2011). In other terms, knowing landscape values by adopting indirect methods such as CVM, DCE, etc., landscape impacts could be assessed by subtracting to the values of the natural asset under pristine conditions the economic values of the asset not destroyed by fire that recovers to over time to a condition close to the original landscape quality. Models of ecological resilience are provided in chapter 6. In Román et al (2013) the recovery from damages to ecosystems is considered by discounting the monetary value of the flow of the residual services after occurrence of a wildfire over time required by the forest ecosystem to return it its pristine condition. A hyperbolic discount factor (*f*) (Equation 10) can be applied, with a low discount rate (*r*) of 2% (Pettenella et al., 2008), and a period of time (*n)* as expression of the vegetation recovery. Consequences of using different discounting approaches on estimated values are explored in the UK Treasury Green Book (HM Treasury, 2022).

Equation 10: Hyperbolic Discount Factor

$$f = \frac{1 - (1 + r)^{-lnn}}{r}$$

The NVC can be also expressed as the reduction on rate of visitation of landscape affected by different fire intensity levels (Molina et al., 2018). In terms of visits frequency, Molina et al. (2009) found that the presence of tourists declined annually from 2.04% to 76.67% in Andean landscape and from 68.13% to 91.01% in Spanish area, by increasing the fire intensity and damage. The landscape susceptibility may be calculated as the product between the maximum landscape damages and the depreciation rate or change in the preferences as expressed by visitation rate in the burnt area.

Figure 24 shows a vulnerability framework that includes burn probability for potential landscape damages in response not only to economic criteria but also to probabilistic risk criteria or landscape vulnerability approach (Molina et al., 2017). This methodological approach includes a conversion of the landscape quality to monetary units expressed as landscape susceptibility, and finally the estimation of landscape vulnerability according to the integration of landscape susceptibility with burn probability.

Finally, not all values emerging from a landscape analysis can be monetised. Loss of traditional livelihood can be considered too, sometimes being more important than the damage of physical and

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aesthetic characteristics of the landscape. Individual´s perception and the identity or familiarity of the landscape can, in fact, change drastically after large fires occurrence (Ojeda et al., 2021). These additional values can be accompanied with the selection of restoration and management actions by involving communities, researchers, and practitioners, also considering climate change and vegetation resilience in the valuation framework.

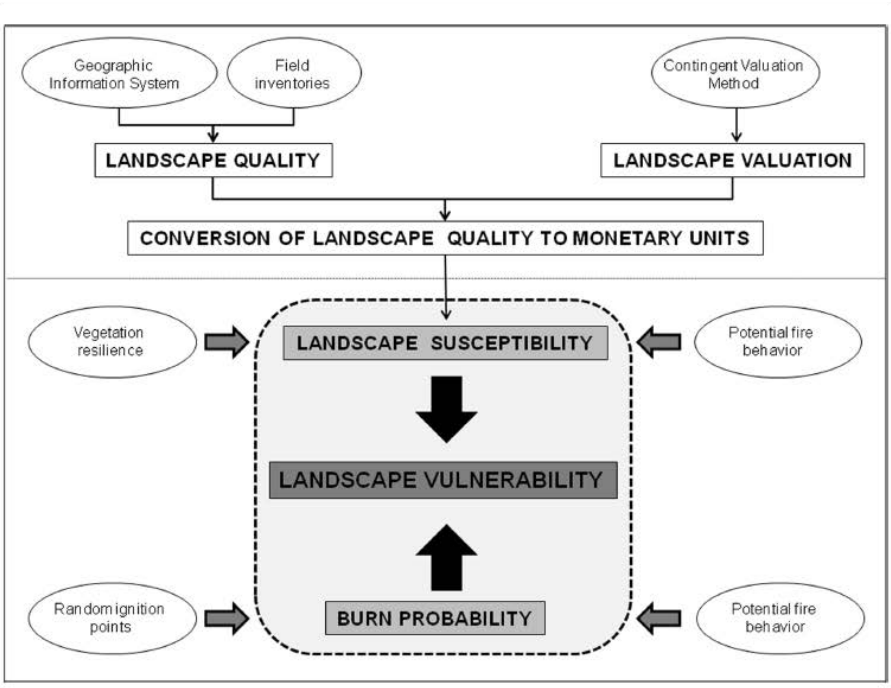


Figure 25: Landscape vulnerability framework. As an example, while landscape susceptibility of "Aracena and Picos de Aroche Natural Park" ranged from 7,116,128 euros to 20,732,613 euros, landscape vulnerability varied between 412,000 euros and 1,200,000 euros (Molina et al., 2017)

7.3.4 Analysis of Human Capital

The term human capital refers to the multiple aspects of the human condition such as skills and knowledge, including being healthy and alive. It also refers to the productive wealth embodied in labour (Dasgupta, 2021). In the context of wildfires, the loss of manufactured assets and natural capital implies the shutdown of many economic activities and the consequent loss (mainly for a period) of labour force and productivity (Wang et al., 2021). Being the value of goods produced related to the productivity in a wage labour economy, the highest impacts of wildfires will be measured in those economies that are healthier and more educated.

The value of human capital in the wildfire context can be measured considering the investment in knowledge and skills to counter the effect of wildfire damages. Countries adopt institutional frameworks and invest in the capacity of firefighters to reduce the damages of fires on the ground and from air, facilitate new measures for the management of land (see social capital) and raise knowledge and skills in populations affected frequently by wildfires on how to escape from dangerous situations. This dimension is not relevantly explored to our knowledge.

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An important element that is more commonly assessed is the damage to health, value of a life or change to life expectancy following wildfires. Pollution caused by wildfire can lead to premature death (mortality), but not rarely to physiological problems causing mental disorders and physical growth disfunction, as well as respiratory and cardiovascular diseases (Liu et al., 2015). Several methods can be used to quantify in monetary terms these impacts, focussing on cost of medical treatment and hospital admittance (Stanke et al., 2013), willingness to pay for avoiding respiratory disease (Jones, 2018; Leslie et al., 2013) and mitigating smoke exposure (Haider et al., 2019), and analysis of costs and quality-adjusted life years (QALYs) under alternative scenarios (Mohammadi et al., 2021). The following sections review some research focussing on the value of health.

7.3.4.1.1 Health values

This section highlights the valuation methods deployed by studies on wildfire smoke health costs. A 'complete' valuation of wildfire impacts is necessary for policymakers to fund fire management strategies appropriately and sufficiently (Richardson et al., 2012; Jones, 2018). A comprehensive valuation of wildfire damage must incorporate the cost of damage to health from wildfires (*ibid*). However, few studies provide reliable estimates of the individual cost of exposure to wildfire smoke (Jones, 2018). The methods covered by these studies include Benefit Transfer Method, Contingent Valuation Method, Cost-Benefit-Analysis, Cost of Illness, Defensive Behaviour Method and Life Satisfaction Approach (see Jones et al., 2016; Jones, 2018; Richardson et al., 2012; Richardson et al., 2013; Tan-Soo & Pattanayak, 2019). Below we briefly describe some of these methods. Key economic valuation methods used by each paper with emerging monetary values are proposed in Table 13.

The most common valuation estimate used by policymakers, economists and health professionals is the 'Cost of Illness' (COI), which quantifies the costs associated with negative health outcomes from wildfires (Richardson et al., 2013). These costs are principally expenditures on medication and medical care, and opportunity cost of time spent obtaining medical care' and lost wages from inability to work (Richardson et al., 2012). However, the COI estimates have been criticised as risking the underestimation of the cost of exposure to pollutants due to the exclusion of the costs of averting and/or mitigating behaviours and disutility (Richardson et al., 2012; Richardson et al., 2013; Jones et al. 2016). Accordingly, alternative methods can be used to calculate the value of health such as the defensive behaviour method that looks at the defensive actions individuals take to measure the economic value of a decrease in symptoms, or the contingent valuation method, used to estimate the value people place on a specific change in a nonmarket good, for instance a decrease in the number of symptom days experienced as a result of exposure to some pollutant (Richardson et al., 2013; Jones, 2018).

In the defensive behaviour method (Richardson et al., 2012; 2013), preferences are elicited by using an approach that reveals the behaviour of people in taking action to reduce illness. In mathematical terms the problem can be solved by finding where the marginal benefit of reduced time spent sick equals the cost necessary to reduce the sick time. Economists, to solve the problem, build a production function (Equation 11), a mathematical relationship where the health output, for instance a number of days with symptoms (*S*), is a function of exposure to pollutant (*P*), exogenous factors that affect symptom days (*Z*), such as lifestyle, demographic factors and health status prior to exposure, and defensive actions (*D*) that serve to decrease symptom days by decreasing exposure to a given pollutant

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(e.g., "evacuating a polluted, area, staying indoors, using a home air cleaner to reduce indoor pollution levels, or using preventative medications such as a prescribed inhaler" - Richardson et al., 2013, p. 77).

Equation 11: Production Function

$$S = f(P, D, Z)$$

The optimal quantity of defensive actions can be found where the individual chooses defensive actions to minimize defensive expenditures, subject to producing a given amount of symptom days, defined by the health production function. Equation 11 is used to identify the optimal level of defensive behaviour and to measure the shadow price, also called the marginal cost of implementing averting behaviour. The latter is the economic cost (different from financial expenditure), of reducing the symptom days up to the point that the economic agent gets maximum utility balancing the costs and the benefits of limiting symptoms.

Whilst such estimates are claimed to be more representative, further research is needed to evaluate and refine these alternative methodologies for valuing wildfire smoke health costs, in comparison to WTP and COI estimates (Jones, 2018; Jones et al., 2016; Richardson et al., 2012; Richardson et al., 2013).

Estimating these values is not easy and requires a long investigation. One possibility to make a "speedy" valuation is by using a benefit transfer approach. The method uses data from one site or context and transfers this to a different (yet ideally similar) context (Jones et al., 2016). A more robust result can be obtained transferring a dose-response function rather than a single value. For instance, Jones at al. (2016) employed a benefit transfer function to estimate the wildfire smoke health cost of the Wallow mega-fire (Albuquerque, New Mexico). They found that the economic costs of a wildfire smoke event are much higher if wildfire dose-response function is used in place of an urban air function, showing that urban-air source data may underrepresent estimates of wildfire smoke health cost (Jones et al., 2016).

Table 13: Monetary values relating to health emerging from the papers reviewed.

Author	Value at stake	Valuation method	Geographic area	Monetary value	Unit	Year of the study
Jones et al.	health	Benefit transfer method using BenMAP-CE, defensive behaviour method, cost of illness, willingness to pay	Albuquerque, New Mexico	COI $74,000 – $111,000 WTP $338,000 – $429,000 for Albuquerque metropolitan area	Dollars (total value for entire community)	2016

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Richardson et al.	health	Defensive behaviour method, willingness to pay, cost of illness	California, USA	COI $9.50, WTP $84.42 per person per exposed day	$/person *exposed day	2012
Tan-Soo et al.	health	Social-cost-benefit analysis	Indonesia	$392 lifetime income loss per person	$/person	2019
Jones	health	Life satisfaction approach, willingness to pay	USA	WTP $129 per person per exposed day	$/person * exposed day	2018
Richardson et al.	health	Cost of illness, defensive behaviour method, contingent valuation method, willingness to pay	California, USA	DMB WTP $86.87 CVM WTP $95.03 COI $3.02 – $16.87 per person per symptom day	$/person * symptom day	2013

7.3.5 Analysis of Manufactured Capital

Manufactured or built capital refers to the human made goods and financial assets that are used to produce goods and services consumed by society. In the specific context of wildfires, we refer to infrastructure and properties and common methods employed to value them.

Wildfires can have a direct effect on houses and infrastructures particularly those situated in the wild land-urban interface (Román et al., 2013) and thus on their price. From this perspective market prices appropriately represent the use value of buildings. To assess damage of fires in wildland urban interface for Spain, Román et al. (2013) used housing prices at municipal level considering centres of populations having more than 25,000 inhabitants. Values of buildings in small municipalities, for which specific data was not available, were assumed to be like the closest municipality with data.

However, it is not correct to assume that wildfires cause the complete loss of the properties at stake. Statistics show that under severe conditions of fire, residential locations might lose 80% of their value (Thompson et al., 2011), depending the damage on the material used for construction (roof and siding) and the proximity to dangerous topography. Another caveat is represented by the value of land. Price of the houses incorporates value of land; thus, damage estimation requires to subtract from the value of the house the part corresponding to land (Román et al., 2013).

An alternative approach to building damage valuation consists in the analysis of price sensitivity to fire damage or to the perceived risk of fire. If wildfire is perceived as a risk, this is incorporated in transaction costs and thus higher prices should reflect the willingness for a reduced risk to fire, along with most common structural characteristics of the property, neighbourhood (presence of schools, playground for children, etc.) and environmental variables (distance to park, forest, lakes, etc). As

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regards variable explaining wildfire risk, it is possible to consider the view of fire, the size of fire, or the distance from wildfire burnt area (Stetler et al., 2010).

Hedonic property models are commonly applied in the environmental economics literature to estimate values of environmental amenities or hazards. Hedonic price methos (HPM) are revealed preference methods of non-market valuation and use housing price data to estimate implicit prices of environmental hazards or amenities not commonly bought and sold in markets. Within hedonic property analysis, a regression is estimated predicting sale price of a home as a function of a set of relevant control variables and the environmental variable of interest. The estimated coefficient on the environmental variable of interest is the "marginal implicit price" of the non-market amenity or hazard (Mueller & Loomis, 2014).

A standard HPM based on a linear regression model between house price and landscape amenities and wildfire risk is proposed by Stetler et al. (2010) who revealed that environmental amenities, including proximity to lakes and national forests, have large positive effects on property values in northwest Montana, while proximity to and view of wildfire burned areas has had large and persistent negative effects on home values. It is evident that homebuyers may correlate proximity to, and view of a wildfire burned area with increased wildfire risk. However, when a fire or a burned area is not visible, and therefore not perceived, the price is not reflecting any risk and the potential loss associated to the lack of information causes an increase in the value of the lost property.

A HPM model based on a quantile regression analysis is proposed by Mueller & Loomis (2014). Compared to the standard OLS regression, quantile regression estimates a range of marginal impacts for different quantiles of the distribution for the dependent variable, consequently providing a significantly more "complete picture" of the true impact of the explanatory variable (Koeneker and Hallock, 2001). Mueller and Loomis (2014) found that the impact of a wildfire differs significantly across the distribution of house prices, and that OLS under-estimate impacts relative to the median quantile, yet over-estimate impacts for lower quantiles.

Finally, Kiel and Matheson (2018) estimated the extent to which damaging fire may have increased homeowners' perceptions about the risk of living in forested areas subject to wildfires. Utilizing a difference-in-difference approach, the authors tested whether buyers of houses in areas at risk of wildfire most likely experiences a statistically significant decline in sale price compared to houses in non-risky areas. In Kiel and Matheson (2018) the hedonic regression is corrected to consider for both a treatment and a control group of houses the effect on prices caused by a change in wildfire risk. To achieve this, a categorical variable taking account for low to very high risk is included in the regression analysis, with the "low" category serving as the omitted variable in the regression; and a dummy variable specifying if the transaction is happened before or after the wildfire. Four different groups are analysed: the control group before and after the event, and the treatment group before and after the event. The estimate of the impact of the event on house prices is the difference in the average prices between the two groups before and after the event. The regression results suggested that buyers' perceptions do change in response to a wildfire. It appears that the buyers that are most impacted are those in the very high-risk areas.

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These examples suggest interesting implications for policy making. Results from HPM can be used to inform debate about efficient allocation of resources to wildfire preparedness, including public education programs, and suppression activities around the wildland–urban interface. In particular, Mueller & Loomis (2014) study indicates that a quantile regression approach can provide policymakers and researchers more information about the marginal implicit price in hedonic models as it relates to the distribution of the dependent variable.

7.3.6 Demonstration of some common values affected by wildfire

This section presents a brief analysis of the most relevant economic values negatively influenced by wildfires (properties, agricultural assets, and some regulating ecosystem services) at European territory scale. Values generated by capital assets proposed in Table 14, listed on the left side of the table, are a measure of the net present value of the flow of benefits generated by the asset itself in perpetuity (e.g., the value of the stock as described in the account (5) proposed by UN SEEA_EA (UNCD, 2021)). Conversely, regulating ecosystem services, listed on the right side of Table 14, are values reflecting annual benefit. Capital values can be considered as a reduction in welfare under the circumstance that the natural and manufactured assets are fully lost without any possibility of recovery. Quantified for the whole European territory, and mapped at scale of 1km2, they provide a measure of economic vulnerability. When integrated with the hazard probability, these values provide a real picture of the likely expected damage for each of the asset below reported. Thus, the vulnerabilities shown below are an essential measure to prioritise those areas that require more investments either by increasing suppressing measures or coping capacity.

Table 14: List of natural capital monetised in €/ha and flow of regulating ecosystem services assessed in €/ha year for the European Territory both valued in 2021 prices

Natural capital (€ /ha)	Regulating ecosystem services (€ /ha per year)
Fruit trees	Pollination
Olive groves	Soil retention
Timber	Water purification
Vineyard	Flood control
Properties	
Cattle	
Sheep	

Detailed Information on the methods used to values the natural assets reported in Table 14 is provided in the Appendix C, along with the key elements explaining the methods used to attribute a monetary value to the regulating ecosystem services. Details on the methodology used to value regulating ecosystem services is provided by JRC and available in the INCA website: Output Data | INCA Platform (europa.eu)

We have extracted from the INCA platform values of ecosystem services originally sourced in euros per Km^2 in 2018 currency, and then rescaled in euros per hectare and corrected in 2021 constant price by the consumer price index of the Euro zone, available in the OECD database (+4.8% in 2021

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compared to the 2018 values) (https://data.oecd.org/price/inflation-cpi.htm). As regards the natural capital (agricultural and forestry provisioning services) and property values these were obtained by combining different sources of information.

EUROSTAT was consulted to provide information on their physical quantity for the European territory at NUTS1 and NUTS2 scale. Additional sources, both grey and peer reviewed literature, were used to reconstruct the monetary value of one hectare of land. Visualization is obtained combining the values per hectare of the asset reported in Table 14 at NUTS1 and NUTS2 with the corresponding habitat/use mapped by the Corine land cover, while for timber it was used the fuel map created within the FirEUrisk project (Aragoneses et al., 2022). More complex is the methodology used to assess the value of properties. These values emerge by multiplying the average national prices reported in the website NUMBEO for properties located outside the centre of the cities to the local to national GDP ratio. Local GDP is a measure of the per capita income in the EU territory mapped at 1 km^2 by Kummu et al (2018), corrected by the population density, while national GDP is the measure of the added value of the national economy. By correcting the average national price of properties proposed by NUMBEO by the GDP ratio we assume that property prices follow linearly the variation of GDP thus guaranteeing the generation of a database characterised by high granularity.

Finally, this information was filtered for the localization of properties located in the Wildland Urban Interface using the European WUI generated within the project (see chapter 5) to provide a spatialization of the properties that can be more likely affected by wildfires. Details on the methods used for valuing and mapping each capital at stake is reported in the Appendix C along with the entire set of maps produced to assess the economic vulnerability. The figures reported below show the values resulting from the sum of all the socio-economic values and ecosystem services, respectively.

As shown in the Appendix C, certain values such a timber (mainly proxied by softwood) are commonly spread across the European territory, with the most valuable assets present in central north Europe reflecting capital values above € 30,000 per ha. Fruit trees are equally spread with a lower density than timber across Europe and very high values in some hot spot between France, Germany, and Italy, where this asset is valued from € 50,000 to € 120,000 per ha. Much more limited is the extension of olive groves and vineyard, with olive trees highest values located in the southern and eastern part of Spain (between €20,000 to 30,000 per ha), and highly valuable vineyard in eastern France, northern and southern east part of Italy and central-eastern part of Germany where values range from € 40,000 to € 80,000 per ha.

In proposing a suitable dataset of economic vulnerability to wildfires, we have removed the annual benefits provided by seasonal crops, usually not much affected by wildfires because of the mismatch between harvesting and wildfire season. There are other assets that can be of high local value, such as non-timber forest products like mushrooms and truffles, and in some local areas characterised by the presence of *Quercus* species, the production of cork. These assets are not captured by EUROSTAT and therefore not reported in our investigation.

The livestock variable (sheep and cattle) is calculated by using a global database published by FAO corresponding to the number of heads per square km in 2010. This value was multiplied by a capital net value per head of 150 euros and 100 euros for cattle and sheep, respectively, and assumed

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uniform for the entire European territory. Details on the generation of these values are provided in the Appendix C. The spatial distribution of cattle varies throughout Europe, but it is possible to appreciate areas with higher concentrations corresponding to those areas with higher production.

Finally, the most valuable economic asset is represented by properties. Excluding the central cities where the risk of wildfires damage is very low, most of the countryside and wildland urban interface is characterised by values between a few hundred euros to € 1,000 per square meter. This range of values reflects not only the built infrastructure but also the value of land, usually not damaged by fire. In addition, these values of properties are assumed to be the worth in case of complete loss of the asset, although it is shown that only in case of extreme fires the entire value of the property can be lost (Román et al., 2012).

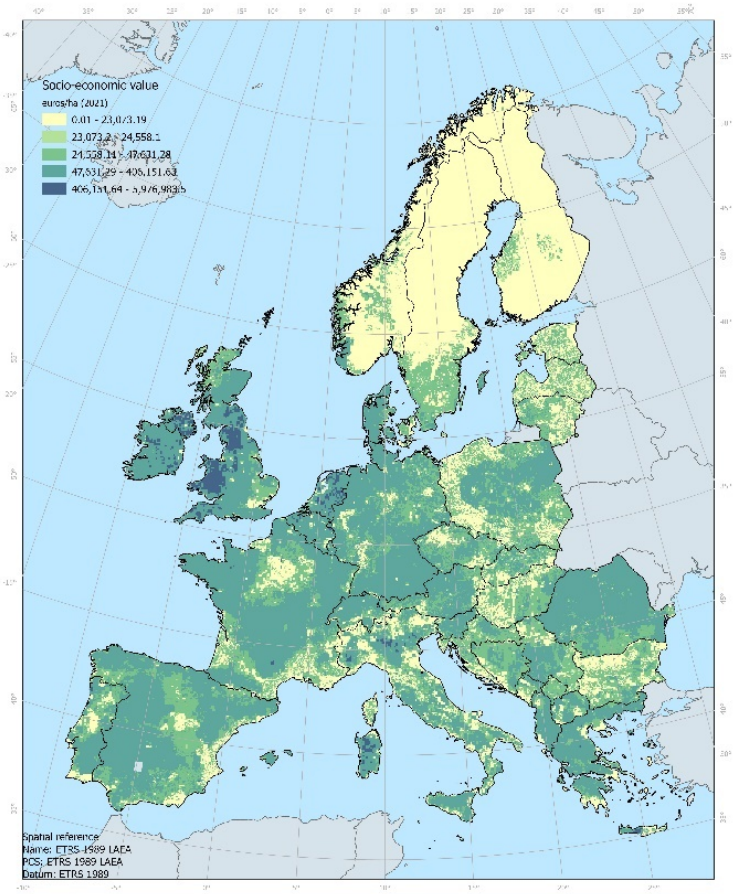


Figure 26: Representation of the socio-economic values at ET scale in euros/ha for 2021. Including timber, fruit groves, vineyard, olives groves, property value and livestock

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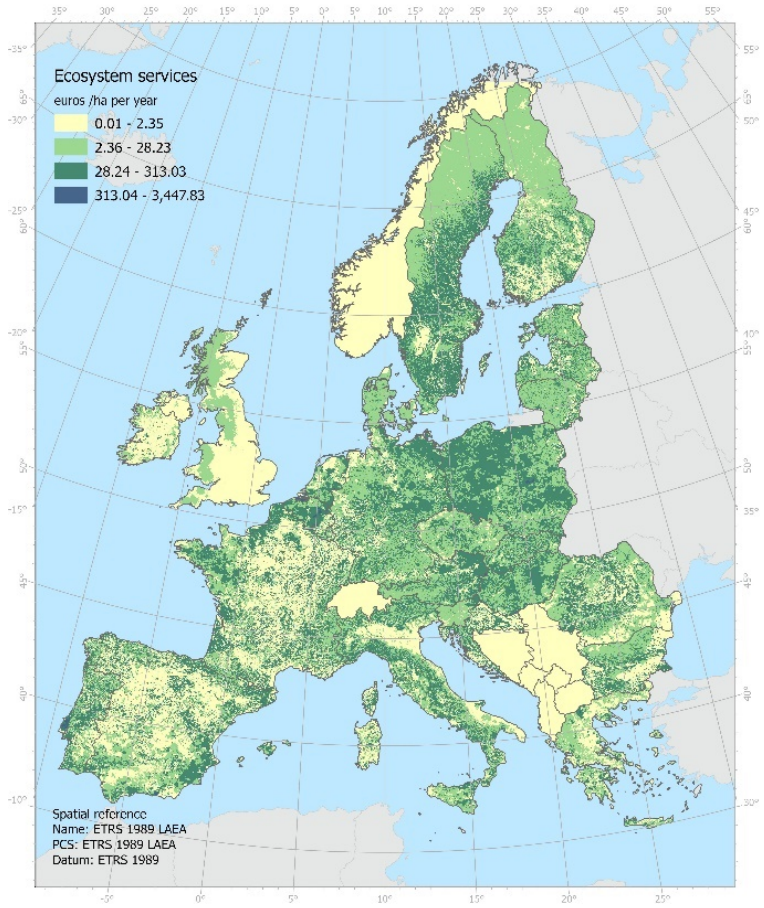


Figure 27: Representation of the regulating ecosystem services values at ET scale in euros/ha for 2021. Including carbon sequestration, crop pollination, flood control, soil retention and water purification

The Figures 25 and 26 propose aggregated monetary values of all the assets and regulating ecosystem services reported in the Appendix C. From the Figure 25, it is possible to observe that the United Kingdom, Belgium, and the Netherlands have the highest spot values, mainly influenced by the high concentration of cattle (see the green and blue spot areas). There are other geographic areas of extreme value, such as those marked in light yellow and green in Spain, France, Germany, and Italy that are influenced by the presence of valuable perennial crops. The average European value for all the agricultural assets considered in this analysis is € 66,000/ha. Figure 26 reports values of ecosystem services. Benefits generated by the regulating ecosystem services seem distributed more evenly than agricultural assets values, with figures up to € 3,500 /ha. The regulating ecosystem service that provides the average highest value is represented by carbon sequestration € 48/ha, while the average lowest value is provided by soil retention with only € 0.5/ha. These low values are justifiable by the reduced capacity of habitats in large portion of the EU territory of generating regulating services, although high values are provided by flood regulation and crop pollination in some areas of Portugal, Belgium, The Netherlands, and Poland. An intermediate value for all these regulating ecosystem services is in the order of € 1,500/ha, and as shown by the yellow-green shaded areas of Figure 26 particularly distributed in the central part of Europe.

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7.4Discussions and Conclusions

This chapter has explored how to analyse wildfire economic vulnerability by implementing the TEV framework within the natural capital-ecosystem services cascade model and emphasised the impacts that wildfires have on multiple capitals (natural, manufactured, human) focussing on the most common typologies of monetary values explored by the economic analysis. This has been done building on a range of examples proposed by recent studies globally distributed.

The analysis of the literature showed that there is a vast use of economic methods to assess both direct impacts to socio-economic activities (e.g., agriculture and forestry), mainly adopting the market approach, and indirect valuations based on analysis of revealed and stated preferences for intangible benefits provided by ecosystem services (e.g., landscape amenity values, recreation, etc.). Benefits that are not marketed (e.g., regulating services, recreational values) are valued by eliciting human preferences under the utilitarian framework adopted in neoclassical economics as marginal willingness to pay for their provision.

From the cases evidenced by the reviewed literature we have found both the use of economic valuations implemented through contingent valuation methods, where interest is the global value of the good (e.g., health, life, habitat, ecosystem, biodiversity, etc.), and through choice experiments where the environmental good (e.g., forest ecosystem or an entire watershed) is split in attributes (landscape amenity, water quality, cultural value of the area, etc.) of which we want to assess the marginal benefits.

Approaches based on analysis of costs rather than benefits, that could be employed for valuing soil fertility loss by wildfires through the replacement of chemical or organic products, or damage to water quality by assessing the expenditures to remove dissolved organic matters, are sparsely used. There is not much evidence in the literature of these values in the context of wildfires although, as shown, there is a florid literature exploring them as ecological values or ecological properties change such as water quality and soil fertility degradation. An example used recently by the European Commission for the Pan-European wildfire risk assessment (Jacome Felix Oom, 2022) refers to the possibility of valuing vulnerability as the cost of restoring land to its former state after wildfire damages (Oehler et al., 2012). Finally, there are other impacts that are rarely considered in the literature such as macroeconomic damage to economy sectors or effects on jobs (Wang et al., 2021).

In the examples proposed in this chapter it emerged how the full potential loss of the asset at stake is rarely achieved after wildfires and a depreciation value is provided using the analysis of net value change of the asset recovering over time (resilience). When addressing the problem of valuation, it is relevant to consider how ecosystems react to wildfires: for instance, different species of trees have a different response to extreme fires and present different mechanisms of recovery that can revert the ecosystem to the pre-damage situation. This capacity of the forest ecosystems to resist and recover (resilience time to pre-fire status) can be modelled considering them as an economic asset whose value is affected by the interest rate used to discount their future values from the time damage occurs to the end of its economic cycle (i.e., the period that in a non-commercial forest can be seen as the time from the manifestation of wildfires to the resprouting of new vegetation and finally the reach of the climax or, in case of a commercial woodland, the end of the rotation period).

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The majority of the examples found in the literature refer to economic vulnerability analysis carried out at local scale. This is the most relevant scale to implement an in-depth analysis with special focus on recreational and human values (e.g., life and health). The analysis of damages to agricultural assets like crops or perennial fruits, and real estate can be consistently addressed as shown in the proposed demonstration at higher scale (1 km^2 for the European territory). This information can be usually generated by combining several sources such as statistics from EUROSTAT that provides biophysical units and, in some cases, monetary values of produced goods, with additional sources coming from more specialised economic studies and geospatial mapping as detailed in the Appendix C. The integration of GIS and ecosystem services analysis has contributed to the generation of values of ecosystem services at multiples scales (targeting mainly the national and supra national tier), as verified for the EU INCA project. Although at EU territorial scale values are usually provided with a coarse resolution of 1 km^2, this valuation can be important to understand where the most valuable assets are located to address more economic resources through increasing suppression or coping capacity.

Operating at coarse scale can make it difficult to integrate information that is locally relevant such as specific provisioning services or cultural, human, and social values, all relevant in complementing the analysis of the economic values proposed in this chapter, if the goal is to provide an exhaustive and integrated pictures of all the capitals affected by wildfires. Although the socio-economic damages to natural and human assets are considered relevant, we must state that the correct analysis of the economic vulnerability is possible only considering the capacity of the society to react to and cope with wildfires. In other words, the vulnerability to wildfires is also affected by the societal resilience to the damage suffered. Institutions can be empowered to strengthen their capacity by operating along different lines, from facilitating the suppression of fire, to reducing the probability of ignition by promoting educational campaign, to mitigating the damage of fire through the implementation of strategies based on more accurate fuel management (e.g., silvicultural treatment, fire breaks, water pools, etc.), conducted at the scale of households, community and landscape. These additional elements are often ignored in the analysis of vulnerability and justify the need to consider multiple domains in the analysis of the socio-ecological system rather than just considering the impact on the capitals that can be valued by a monetary metric approach.

Only the integration of the full set of capitals proposed in this report has the advantage to make use of a more holistic thinking perspective of how a wildfire event can affect society and how institutions and communities can react to address the problem. The integrated approach by its nature involves understanding both impacts and dependencies on a wider group of stakeholders. This requires collaboration with local groups, business, NGOs, government, and academics. While the review provided in this chapter feeds into this integration, only the interactions between all these parties can facilitate knowledge exchange to understand impacts and develop those synergies necessary to counteract wildfire

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8. Conclusions and Recommendations

8.1 Summary of results

This report and (and related proposed methodological frameworks) aim to advance scientific knowledge on the various approaches to fire vulnerability assessment. The main FirEUrisk's objective that this report aims to contribute refers to O2 “Update current methods of fire risk assessment to integrate socio-economic and ecological impacts of wildfires”.

The achievement of this objective – which ultimately aims to improve Risk assessment framework - is corroborated by efforts implemented around the following project deliverables:

- (D1.5) The setting up of geodatabases on the fire exposure & vulnerability
- (D1.6) The development of an on-line methodological handbook for socio-economic assessment of fire impacts and damages.

Within this scope, the report presents a review of the contemporary scientific understanding of the major components that affect the vulnerability of both socio-economic and natural systems to wildfires; moreover, the report aims to contribute to innovating conceptual approaches to evaluate exposure and vulnerability, so to facilitate the subsequent integration of these disparate components into a unified framework of fire risk assessment in Europe (i.e., contributing thus to the overarching goal of the project of developing an integrated strategy for strategy for fire risk assessment, reduction, and adaptation).

The proposed methodological frameworks and related analyses cover all three major components of wildfire vulnerability (societal, ecological/environmental, and economic). Moreover, because there is no vulnerability without exposure (as exposure forms the link between wildfire hazard and vulnerability), the report also addressed the subject of wildfire exposure, while accounting for its two main components: direct exposure to fires as well as exposure to smoke emitted from wildfires. Where feasible, the report provides guidelines (with practical examples in different parts of the EU, or even at the scale of the entire European territory) to the development of both qualitative and quantitative methods to estimate exposure and vulnerability. These quantitative methods provide metrics and indices which form the foundation of an integrated wildfire risk assessment approach that links hazard, exposure, vulnerability, and prevention in a practical manner, and, in turn, may inform and enhance the EU’s fire risk prevention and adaptation policy.

The analysis of fire exposure (Chapter 3) utilised two different yet related methodological approaches, which both combine the two main aspects that dictate where values-at-risk might be affected by wildfires: the potential spatial distribution of fires, and the geographic locations of values-at-risk (be them houses, other property, infrastructure, or natural elements). The difference between the approaches is the source of data on the spatial distribution of fire occurrence. In the first (3.2.1), it is derived from fire spread simulation models, and in the second (3.2.2) it is derived from fire weather indices (FWI). In either approach, spatially explicit estimates of exposure are calculated using a geospatial analysis as the juxtaposition of the outputs of fire spread models or meteorological models of FWI (the former predict fire characteristics such as fireline intensity, rate of spread, atmospheric emissions, and smoke; the latter predict classes of fire danger), with

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101003890.

expansive datasets of values at risk (residential structures, road networks, human population, and protected areas). The final output of this analysis is fire exposure potential to a specific wildfire characteristic (e.g., PM10 emissions) for a given value at risk (e.g., residential structures). The chapter exemplifies this approach in study areas in Barcelona (Spain) and Attica (Greece). The outputs of these analyses highlight areas of high potential exposure to wildfires, which should be the focus of subsequent analyses of vulnerability.

The analysis of societal vulnerability to wildfires (Chapters 4, 5) comprised three components due to the complexity of the issue and the plethora of approaches to describe and assess vulnerability to natural hazards in general, and to wildfires. Within the scope of this research activity, first a thorough literature review was conducted to synthesise the many different views about social vulnerability to wildfires (4.1). Following, a methodological approach for estimating vulnerability at the local scale is presented (4.2). Finally, a methodology for mapping the wildland-urban interface is introduced (Chapter 5). As the subject lies at the intersection of exposure and vulnerability, it was discussed separately from the main analysis of both exposure and social vulnerability. The WUI methodology was applied across the entire European territory to provide the first high resolution wall-to-wall maps of the European WUI (5.3), focusing on woody vegetation while omitting grasslands. The focus on woody vegetation was driven by management consideration, as woody fuels pose, one average, higher fire hazard while also being more difficult to manage. In general, the review of the current state of the science of social vulnerability to wildfires revealed that the relative approach is the most suitable when dealing with a complex set of phenomena which contribute to the overall increasing or decreasing of vulnerability at a community level. Beyond the literature review, an operational approach to assess social vulnerability indicators and proxies composing a relative social vulnerability index (ReSVIs) was proposed. The methodology which supports assessments at the community level and was implemented to different extents in 4 out of 5 Pilot Sites. The index is based on assembling a (relevant/context-specific) set of indicators and proxies for societal vulnerability based on participatory approaches with relevant stakeholders at community and regional levels. In this approach, both the suitability of the indicators/proxies, the feasibility of collecting quantitative data on them, and their relevance to social vulnerability are assessed. Then, a quantitative approach is used to calculate ReSVI at the community level, with this index reflecting the relative vulnerability of a given community in a given aspect, compared to other communities. ReSVI can be used either looking at the single dimensions (per aspect of vulnerability, i.e., social, economic, institutional, human capital, environment) or as an aggregate (based on averaging) to provide comparable quantitative measures of social vulnerability at different units of analysis. These, in turn, serve as inputs to higher-level integrations of vulnerability, and fire risk in general.

The quantitative assessment of environmental vulnerability (Chapter 6), which focused on ecological vulnerability to wildfires, is an extremely challenging endeavour due to the overall complexity of ecological systems and to the scarcity of data regarding resilience to fire (particularly for non-fire prone regions). Consequently, the proposed conceptual framework for quantifying ecological vulnerability (6.1) accounts for the main mechanisms developed by species in vegetated ecosystems to respond and resist to wildfires. The chapter puts specific emphasis on plant regeneration strategies, as these drive the trajectory of post-fire recovery at the individual, population, and ecosystems levels, with their associated ecosystem functions. Consequently, the proposed framework for quantifying ecological vulnerability to wildfires in vegetated ecosystems accounts for the following processes, each of which can potentially be quantified empirically to support a quantitative analysis: potential loss by fire, which is the sum of actual loss and resistance; recovery

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time, rate, and growth time, together with regeneration time. All these variables are ecosystem (and species) specific, which makes their quantification exceedingly difficult in real settings. Still, there are many existing datasets on various ecosystem characteristics such as soil types, species composition, aboveground biomass, net primary productivity, species diversity, and more (6.2). Using these as indicators of ecosystem state (and estimating their response to fires) facilitates the calculations of specific measures of ecological vulnerability (6.3), and their subsequent integration (via weighted averaging) into increasingly coarser measures of ecological vulnerability, in a manner similar to what the report suggested to do with ReSVI's in the context of social vulnerability.

Hence these new indices of ecological vulnerability could also serve as inputs into integrated assessments of vulnerability, exposure, and danger to obtain comprehensive evaluations of risk.

In the context of economic analysis (Chapter 7), the literature review (7.3.1) proposed a multiple range of values addressing direct uses of natural capital (7.3.2) (e.g., timber, non-timber forest product, agricultural assets, recreational value of park) and indirect values provided by ecosystem services (e.g., carbon sequestration, amenity values of landscape), as well as monetary impacts on human health (7.3.4) and infrastructures (7.3.5). These studies reveal that an integration between the Total Economic Value framework and the natural-capital ecosystem services cascade model (7.2) can be used to assess the utilitarian values (or welfare) of goods and services provided by natural, human and manufactured infrastructure by employing a range of approaches based on market price (where available), and analysis of preferences by revealed and stated methods in those cases where market forces cannot generate a price. To show how to use the proposed economic valuation the chapter proposes to capture in a single monetary metric (expressed in euros per hectare) many direct and indirect use values of natural capital at coarse scale (resolution of 1 km^2) for the entire European Territory with particular focus on provisioning (forestry and agricultural assets) and regulating ecosystem services, and provided maps aggregating these values to depict those areas that might need more economic support if affected by wildfires (7.3.6). The chapter also emphasises that cultural values based on relational aspects of nature embedded in bio-centric/eco-centric views, affecting both human and social dimensions of the relationship between people and wildfire, cannot be measured using a monetary metric, making their integration impossible under the economic domain (in contrast to the approaches we outlined in the cases of societal and ecological vulnerability). In addition, according to the contemporary literature, they are mostly explored at local scale, referring to a specific territorial unit such as local communities. It would be therefore difficult, if not impossible, to upscale them to a higher tier (i.e., the entire EU territory) without the risk of introducing considerable biases. The monetary index of economic assets and ecosystem services can still be used in comprehensive approach integrating the entire set of vulnerable indicators proposed by the ecological and social analysis. This can be achieved by the normalization of each indicator and assignment of a weight by expert consultation to produce a quali-quantitative index unrelated to any dimension. This approach seems a promising solution when operating at coarse scale, while the possibility to observe trade-offs through the analysis of a dashboard of indicators better reflect the goal to find local solutions to the multiple needs emerging when the analysis of societal vulnerability requires a higher granularity assessment.

Finally, the following table aims to summarise how this deliverable contributed to achieve the objectives of WP1:

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Table 15: Contributions of D1.4 in reaching the WP1 Objectives

WP1 OBJECTIVE	CONTRIBUTION by D1.4
To define and validate a unique and integrated risk-based fire management approach across all phases of wildfire issues (prevention, monitoring, preparedness, response, and restoration) towards and integrated wildfire management approach.	This has been addressed in all chapters (sub-tasks/activities of Task 1.2), insofar as investigated (and applied) vulnerability frameworks, set the basis for the further understanding of opportunities and challenges towards an integrated wildfire management approach founded on the risk assessment. Chapter 7 presents data on the economic impacts of fire, including on natural, social, and human capital. This economic assessment feeds into understand of risks of fire.
To identify and map the primary human drivers of fire occurrence and evolution, taking gender and demographic factors into account, to incorporate social-science knowledge with the purpose of minimising human-caused fires and strengthening societal fire resilience.	This has been addressed mainly in Chapters 4 and 7. While social variables (including demographics) and overall variables related to human drivers of fire occurrence are considered in the ReSVI indexes calculation, economic impacts of fire on social capital are explored in Chapter 7, including impacts on employment and health. This estimation of the social capital costs of wildfires provides the economic counterpart to the estimates of societal vulnerability and resilience assessment in Chapter 4. Linking to the mapping of the WUI in Chapter 5 provides an idea of potential scale of the manufactured capital costs of wildfire estimated in Chapter 7.
To advance current fire risk assessment methods by incorporating the socioeconomic and ecological impacts of wildfires, considering the value of all exposed assets, in terms of biodiversity, natural capital (i.e., the natural asset) and the ecosystem services this asset provides.	This has been addressed mainly in Chapters 6 and 7, a well as in Annex A2 – Damage functions review. Economic costs of exposed assets are estimated in Chapter 7, including natural, human, and manufactured capital, and the integration of these economic assessments. The natural capital estimates in Chapter 7 are further contextualised by the environmental assessment in Chapter 6. Annex A2 collected and discussed existing damage functions related to damage of wildfires in infrastructures, including impacts to infrastructure failure due to wildfires and smoke exposure, per sector.
To improve fire risk modelling in wildland-urban and wildland-rural interface areas, including novel methodologies for evaluating non-natural fuel fire behaviour, tactics for reducing fuel loads, increased	This has been addressed mainly in Chapter 5, with a focus on the WUI mapping.

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firefighting safety, and risk-adapted evacuation plans.	
To create a citizen-science approach that encourages local populations to participate in fire control methods that boost rural economies, promote biodiversity, and explore nature-based solutions.	This has been addressed mainly in Chapters 4 and 7. Chapter 4 illustrates the potentiality of promoting a citizens science approach in the assessment of social vulnerability, by means of participatory methods. In fact, ReSVI indexes are created by incorporating the local knowledge of relevant stakeholders (both in the selection of variables and overall calculation – by attribution of different weights based on perceived relevance of the variable within a specific (local) context. ReSVI indexes can be, in fact, further developed and completed by qualitative data derived from participatory processes at local level[35] . Further to the explicit exploration of citizen science in Chapter 4, the economic assessment in Chapter 7 can provide tangible justification to citizens of the importance of their efforts to reduce wildfire risk in terms of avoided economic damages.

8.2 Recommendations for integration

The four different components of this report focus on inherently different facets of vulnerability (and exposure) to wildfires. As such, integrating their outputs to yield a combined assessment of vulnerability which aggregates the dimensions of social, ecological, and economic vulnerabilities is a difficult task. Yet an integrated framework for fire risk like the one being developed in FirEUrisk requires that each component of fire risk (i.e., hazard, exposure, vulnerability, prevention) is a sum of its parts. To that end, the report offers a blueprint to such an integration, based on the existence of some commonalities in the quantitative outputs of these different facets.

As presented above, perhaps the greatest barrier to the successful quantification of any measure of vulnerability is data availability (be it qualitative data from participatory approaches, through ecological data on species traits and forest recovery rates following fires, to the severe shortage of high-resolution economic data across Europe). Hence limiting the integration to those places where fire exposure is high can greatly reduce the geographic scope of the analysis, and consequently limit somewhat the amount of data that needs to be collected. This spatial filtering can be carried out by focusing on WUI areas, intersected with high-exposure values at risk. Then, assuming sufficient data exist (or can be collected), it is necessary to quantify each facet of vulnerability separately, including at first all of its sub-components (i.e., multiple ReSVIs for social vulnerability, different VIs for ecological vulnerability, and various ecosystem services valuations for economic vulnerability). As each of these analyses is expected, in turn, to result in many different

[35] Approach partially implemented inT.1.2.2, and to be further implemented for the purpose of the projects' Demonstration events in the next project period.

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vulnerability indices per dimension, one would need to integrate them into a single measure of vulnerability per dimension using a weighted combination approach depending on the specific interests and needs of the relevant stakeholders. Then, a coarser level of integration will need to be carried out, this time combining vulnerability measures across dimensions, thus resulting in a single measure of wildfire vulnerability, which would ideally be comparable across communities/regions in order to facilitate decision making about resource allocation to reduce vulnerability. Yet it is possible that such aggregation is a disservice to our understanding of vulnerability, as it necessitates the simplification of the inherent complexity of the concept.

A second level of complexity is posed as well by the quantification/measurement vs assessment concepts, especially for some of the vulnerability dimensions studied within the scope of this report (i.e., societal, and economic vulnerability). On one side, Chapter 4 (4.1.2) argues that a vulnerability score (a numerical value that aggregates all the operations performed by collecting values for indicators) gains major significance for interpretation (high or low) by reference (distance) to a mean value, and reference to other units of analysis that comprise this mean. On the other side, Chapter 7 poses criticalities for what concerns the monetisation of specific values such as those regulating ecosystem services that do not have a market and cannot be easily linked to a marketed output, like soil retention and fertility, or water purification.

Moreover, when considering vulnerability analysis from the perspective of strategy design and setting, the proposed methodological frameworks and consulted literature tend to suggest the preference for participatory approaches in which communities (i.e., understood as relevant stakeholders) themselves are involved in the assessment process, so to allow for context-based relevance of resulting strategies.

The work carried out within the scope of Task 1.2 appears thus to recommend a more holistic perspective that by its nature involves understanding of both impacts and dependencies on a wider group of stakeholders.

In carrying out an integrated measure of vulnerability it is possible to plan measures to mitigate wildfire risks by considering not only passive policies based on fire suppression, but active measures based on effective participations of stakeholders and communities supporting the proposal of land use strategies. These may proactively generate return and significant additional benefits such as the protection of wages and jobs through the defence of natural capitals and the resulting provisioning services (wood, timber, NTFP, and other agro-forestry values), along with more immaterial benefits for the entire community generated by regulating services and enhance social networks and trust between local stakeholders.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003890.

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Annex A1: A122 – Societal Vulnerability and resilience assessment: ReSVI Elaboration

Preliminary List of Indexes and Proxies

The following tables illustrate the complete list of indicators and proxies proposed for the analysis of societal vulnerability to all Pilot Sites.

Indicators and proxies which are quoted in fire-specific studies are marked with a (*).

Social Dimension

Social Dimension Indicators and Proxies

Social Dimension			
Indicator	**Proxy**	**Scale**	**Source / adapted from**
Age*	Percentage of residents aged 65 years or above*	Macro, meso	Burton, 2012, Eidsvig et al., 2011, ENSURE, 2009, Baum et al., 2008, Tapsell, 2005, Oliveira et al., 2020
	Median age	Macro, meso	Baum et al., 2008
	Percentage of population below 5	Macro, meso	Burton, 2012, Eidsvig et al., 2011, ENSURE, 2009, Baum et al., 2008, Tapsell, 2005
	Percentage of young people (< 20 yo)*	Macro, meso	Oilveira et al., 2020
	Percentage of population aged below 15*	Macro, meso	Parsons et al., 2020
	Percentage of population aged over 75*	Macro, meso	Parsons et al., 2020
	Age dependency rate*	Macro, meso	Leone et al., 2003
Communication services*	Internet, television, radio, and telecommunications broadcasters per 1,000 inhabitants	Macro, meso	Burton, 2012, Cardona, 2005
	Percentage of area with mobile phone coverage*	Macro, meso	Parsons et al., 2020
	Percentage of area with excellent or good ADSL service*	Macro, meso	Parsons et al., 2020
Community Capital*	Religious organizations per 1,000 inhabitants	Macro, meso	Burton, 2012
	Professional, scientific, and technical services per 1,000 inhabitants	Macro, meso	Burton, 2012
	Research and development firms per 1,000 inhabitants	Macro, meso	Burton, 2012
	Social advocacy organizations per 1,000 inhabitants	Macro, meso	Burton, 2012

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	Arts, entertainment, and recreation centres per 1,000 inhabitants	Macro, meso	Burton, 2012
	Civic organisations per 1,000 inhabitants	Macro, meso	Burton, 2012
	Historical heritage sites per square kilometre	Macro, meso	Burton, 2012
	Percentage of population with high generalised trust*	Macro, meso	Parsons et al., 2020
	Percentage of population with life satisfaction scale 70 or above*	Macro, meso	Parsons et al., 2020
	Offences against persons per 100,000 inhabitants*	Macro, meso	Parsons et al., 2020
	Offences against property per 100,000 inhabitants*	Macro, meso	Parsons et al., 2020
	Percentage of people undertaking voluntary work*	Macro, meso	Parsons et al., 2020
Family structure*	Average number of people per bedroom	Macro, meso	Baum et al., 2008
	Percentage of people separated or divorced	Macro, meso	Baum et al., 2008
	Percentage of people married	Macro, meso	Baum et al., 2008, ENSURE, 2009, Tapsell, 2005
	Percentage of people who are widowed	Macro, meso	Baum et al., 2008
	Percentage of single parent families*	Macro, meso	Baum et al., 2008, ENSURE, 2009, Tapsell, 2005, Parsons et al., 2020
	Percentage of lone persons households*	Macro, meso	Parsons et al., 2020
	Percentage of households with children*	Macro, meso	Parsons et al., 2020
Gender*	Percentage of women*	Macro, meso	ENSURE, 2009, Tapsell, 2005, Oilveira et al., 2020
	Percentage of men	Macro, meso	ENSURE, 2009, Tapsell, 2005
	Gender-related Development Index, GDI	Macro	Cardona, 2005
Migrations, Race and Ethnicity*	Percentage of the population that is not an ethnic minority	Macro, meso	Burton, 2012
	Percentage of persons born abroad who arrived in the past five years	Macro, meso	ENSURE, 2009, Baum et al., 2008, Tapsell, 2005
	Percentage of the population is not familiar with majority language and culture	Macro, meso	Eidsvig et al., 2011, Burton, 2012, Baum et al., 2008
	Migration effectiveness*	Macro, meso	Parsons et al., 2020

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Social dependence	Social assistance programs per 1,000 inhabitants	Macro, meso	Burton, 2012
Special needs populations	Percentage of the population that is not institutionalized or infirmed	Macro, meso	Burton, 2012
	Childcare programs per 1,000 inhabitants	Macro, meso	Burton, 2012
	Percentage of residents who require assistance with daily tasks	Macro, meso	Baum et al., 2008
Wealth and Socio-economic status*	Percentage of the population with vehicle access*	Macro, meso	Burton, 2012, ECLAC, 2011, Baum et al., 2008, Parsons et al., 2020
	Percentage of the population with telephone access	Macro, meso	Burton, 2012
	Human Development Index	Macro	Cardona, 2005
	Human Poverty Index, HPI	Macro	Cardona, 2005
	GINI coefficient	Macro	Cardona, 2005
	Business and professional organizations per 1,000 inhabitants	Macro, meso	Burton, 2012

Economic Dimension

Economic Dimension Indicators and Proxies

Economic Dimension			
Indicator	**Proxy**	**Scale**	**Source / adapted from**
Wealth and Socio-economic status*	Percentage of home ownership*	Macro, meso	Burton, 2012, ENSURE, 2009, Tapsell, 2005, Parsons et al., 2020
	Land tenure*	Macro, meso	Jucker Riva et al., 2018
	GDP per capita*	National	Eidsvig et al., 2011, ENSURE, 2009, Tapsell, 2005, Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Electricity consumption kilowatt hours / capita/ year	Macro, meso	ECLAC, 2011
	Per capita household income	Macro, meso	Burton, 2012, Baum et al., 2008
	Median individual income*	Macro, meso	Baum et al., 2008, Parsons et al., 2020
	Annual increase in food prices (%)	Macro, meso	Cardona, 2005
	Energy prices*	Macro, meso	Jucker Riva et al., 2018
	Median monthly mortgage repayment*	Macro, meso	Parsons et al., 2020
Business structure	Ratio of large to small businesses	Macro, meso	Burton, 2012
	Retail centres per 1,000 inhabitants	Macro, meso	Burton, 2012
	Commercial establishments per 1,000 inhabitants	Macro, meso	Burton, 2012

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	Mean sales volume of businesses	Macro, meso	Burton, 2012
	Lending institutions per 1,000 inhabitants	Macro, meso	Burton, 2012
	Percentage of commercial establishments outside of high wildfire hazard zones	Macro, meso	Burton, 2012
	Density of commercial infrastructure	Macro, meso	Burton, 2012
	Imports and exports of goods and services as a Percentage of GDP	Macro, meso	Cardona, 2005
Primary sector*	Share of agriculture in total GDP growth (annual %)	Macro, meso	Cardona, 2005
	Percentage of population occupied in the primary sector*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009, Oliveira et al., 2020, Leone et al., 2003
	Energy consumption in agriculture*	Macro, meso	Leone et al., 2003
	Variation of number of owners of agrarian holdings (time span)*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Percentage of owners of agrarian holdings with >55 years*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Density of agricultural machinery (include all kind of tractors, combine harvesters, binders, millings machines, hoe machines, seed drills, etc.)*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009, Leone et al., 2003
	Livestock density in extensive regime (not in stables)*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Livestock density*	Macro, meso	Leone et al., 2003
	Number of pasture licences*	Macro, meso	Leone et al., 2003
	Market prices of goods produced from the land (e.g. wood, cheese or meat, honey, energy etc.)*	Macro, meso	Jucker Riva et al., 2018
	Average market price of wood*	Macro, meso	Leone et al., 2003
	Yearly price of wood variation*	Macro, meso	Leone et al., 2003
	Forest commercial value*	Macro, meso	Leone et al., 2003
	Forest area with low potential forest productivity*	Macro, meso	Leone et al., 2003
	% employed in traditional activities in wildland/rural areas (cattle grazing, firewood extraction, resin and cork production)*	Macro, meso	Leone et al., 2003
Capitals	Social expenditures on pensions, health and education as a Percentage of GDP	Macro	Cardona, 2005
	Capital stock in millions of € per thousand square kilometres	Macro	Cardona, 2005
	Gross domestic fixed investment as a Percentage of GDP	Macro, meso	Cardona, 2005
	Debt service burden as a percentage of GDP	Macro	Cardona, 2005

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Institutional Dimension

Institutional Dimension Indicators and Proxies

Institutional Dimension			
Indicator	**Proxy**	**Scale**	**Source / adapted from**
Emergency response*	Existence of an organisation of emergency response, with coordination authority	Macro, meso	Eidsvig et al., 2011
	Fire and emergency services per 1,000 inhabitants*	Macro, meso	Burton, 2012, Eidsvig et al., 2011, Parsons et al., 2020
	Police services per 1,000 inhabitants*	Macro, meso	Burton, 2012, Eidsvig et al., 2011, Parsons et al., 2020
	Ambulance officers and paramedics per 1,000 inhabitants*	Macro, meso	Parsons et al., 2020
	Temporary shelters per 1,000 inhabitants	Macro, meso	Burton, 2012, Eidsvig et al., 2011
	Percentage of fire, police, emergency relief services, and temporary shelters outside of hazard zones	Macro, meso	Burton, 2012, Eidsvig et al., 2011
	Early warning systems used in coordination with emergency response procedures	Macro, meso	Eidsvig et al., 2011, ENSURE, 2009, Tapsell, 2005
	Number of days of work in fire control activity of seasonal fire fighters*	Macro, meso	Leone et al., 2003
	Shelters per 1,000 inhabitants*	Macro, meso	Oilveira et al., 2020
Risk Financing	Infrastructure and housing insurance as a Percentage of GDP	Macro, meso	Cardona, 2005
	Percentage of the population with Citizen Corps program participation	Macro, meso	Burton, 2012
Risk Mitigation*	Percentage of the population covered by a recent hazard mitigation plan	Macro, meso	Burton, 2012
	Protection and management of forest land*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Percentage of forest surface with less management, control and planning over time[36]*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
Risk Awareness	Hazard maps available	Macro, meso	Eidsvig et al., 2011
	Assessment of direct impacts to exposed populations	Macro, meso	Eidsvig et al., 2011

[36] In the Spanish case: private forest land, land belonging to local authorities with free use, consortiums and neighbouring forest common land.

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	Levels of risk awareness and preparedness	Macro, meso	ENSURE, 2009, Tapsell, 2005
	Previous wildfire hazard experience	Macro, meso	ENSURE, 2009, Tapsell, 2005
Regulations*	Guidelines in place for all constructions and land-use activities to ensure minimal risk to exposed population	Macro, meso	Eidsvig et al., 2011
	Regulation of construction and land use*	Macro, meso	Eidsvig et al., 2011, ECLAC, 2011, Jucker Riva et al., 2018
	Percentage of development projects accompanied by Environmental Impact Assessment	Macro, meso	ECLAC, 2011
	Number of expropriation expedients or actions*	Macro, meso	Leone et al., 2003
Incentives*	Subsidies for land use activity (agriculture, farming, tourism and others)*	Macro, meso	Jucker Riva et al., 2018
	Subsidies for land management or nature conservation*	Macro, meso	Jucker Riva et al., 2018
Governance*	Voice and accountability	Macro, meso	Brooks et al., 2005
	Civil liberties	Macro, meso	Brooks et al., 2005
	Political rights	Macro, meso	Brooks et al., 2005
	Access to decision-making	Macro, meso	ENSURE, 2009, Tapsell, 2005
	Trust in authorities	Macro, meso	ENSURE, 2009, Tapsell, 2005
	Governance Index (Kaufmann)	Macro	Cardona, 2005, Brooks et al., 2005
	Cooperation and community organisation*	Macro, meso	Jucker Riva et al., 2018

Human Capital Dimension

Human Capital Dimension Indicators and Proxies

Human Capital Dimension			
Indicator	**Proxy**	**Scale**	**Source / adapted from**
Educational Level*	Adult education and skills-training programs per 1,000 inhabitants	Macro, meso	Burton, 2012
	Percentage of the eligible population (over 18 years of age) have attended, or are attending, a post-secondary education	Macro, meso	Eidsvig et al., 2011
	Percentage population with elementary school level*	Macro, meso	Oilveira et al., 2020
	Percentage population with secondary school level*	Macro, meso	Oilveira et al., 2020

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	Percentage population with higher educational level*	Macro, meso	Tapsell, 2005, ENSURE, 2009, Oilveira et al., 2020, Parsons et al., 2020
	Literacy rate*	Macro, meso	Oilveira et al., 2020
	Literacy rate (% of population over 15)	Macro, meso	Brooks et al., 2005
	Literacy rate (% of 15-24 year olds)	Macro, meso	Brooks et al., 2005
	Literacy ratio (female to male)	Macro, meso	Brooks et al., 2005
Health Services*	Percent of the population without a disability	Macro, meso	Burton, 2012
	Psychosocial support facilities per 1,000 inhabitants	Macro, meso	Burton, 2012
	Health services per 1,000 inhabitants	Macro, meso	Burton, 2012
	Hospital beds per 1,000 people*	Macro, meso	Cardona, 2005, Eidsvig et al., 2011, Parsons et al., 2020
	Number of doctors and medical professionals per 1,000 inhabitants*	Macro, meso	Burton, 2012, Parsons et al., 2020
	Psychologists per 1,000 inhabitants*	Macro, meso	Parsons et al., 2020
	Population with access to sanitation (%)	Macro, meso	Brooks et al., 2005
	Life expectancy at birth	Macro, meso	Brooks et al., 2005
	Maternal mortality per 100 thousand	Macro, meso	Brooks et al., 2005
Occupation*	Percentage of population dependent on the land for primary source of income	Macro, meso	Eidsvig et al., 2011
	Ratio of skilled and unskilled workers	Macro, meso	ENSURE, 2009, Tapsell, 2005
	Percentage of the population employed as managers and professionals*	Macro, meso	Parsons et al., 2020
	Percentage of the population that is employed*	Macro, meso	Burton, 2012, ENSURE, 2009, Tapsell, 2005, Oilveira et al., 2020
	Male labour force participation rate	Macro, meso	Burton, 2012, Baum et al., 2008
	Female labour force participation rate	Macro, meso	Baum et al., 2008
	Percentage of unemployment from the total labour force*	Macro, meso	Cardona, 2005, ENSURE, 2009, Tapsell, 2005; Martínez, Vega-Garcia & Chuvieco, 2009, Oilveira et al., 2020, Leone et al., 2003, Parsons et al., 2020
	Percentage of the population not employed in primary industry	Macro, meso	Burton, 2012

Environmental Dimension

Environmental Dimension Indicators and Proxies

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Environmental Dimension			
Indicator	**Proxy**	**Scale**	**Source / adapted from**
Physiography*	Elevation (average)*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Oilveira et al., 2020
	Aspect*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Slope (average)*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Topographic roughness*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Soil erosion*	Meso	Jucker Riva et al., 2018
	Soil moisture*	Meso	Jucker Riva et al., 2018
	Soil drainage/infiltration*	Meso	Jucker Riva et al., 2018
	Surface runoff*	Meso	Jucker Riva et al., 2018
Biodiversity (fauna)*	No. of species which have become extinct this century / 10,000 sq. km land	Macro, meso	ECLAC, 2011
	No. threatened, endangered species/10,000 sq. km land	Macro, meso	ECLAC, 2011
	No. introduced terrestrial species/10,000 sq. km land (over last 100 years)	Macro, meso	ECLAC, 2011
	No. of endemic species/10,000 sq. km land	Macro, meso	ECLAC, 2011
	Soil fauna*	Macro, meso	Jucker Riva et al., 2018
	Birds*	Macro, meso	Jucker Riva et al., 2018
	Wild grazers*	Macro, meso	Jucker Riva et al., 2018
	Domestic grazers*	Macro, meso	Jucker Riva et al., 2018
	Predators*	Macro, meso	Jucker Riva et al., 2018
Biodiversity (flora)*	Presence of a mixture of grasses, shrubs and trees (complex vegetation structure)*	Macro, meso	Jucker Riva et al., 2018
	Number of present species (vegetation diversity)*	Macro, meso	Jucker Riva et al., 2018
	Presence of a specific plant or group (e.g. resprouters, palatables)*	Meso	Jucker Riva et al., 2018
	Presence of alien/dangerous species*	Macro, meso	Jucker Riva et al., 2018
Environmental Systems*	Percent land area that consists of windbreaks and environmental plantings	Macro, meso	Burton, 2012
	Percent land area that is developed open space	Macro, meso	Burton, 2012

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	Percent land area that is arable cultivated land*	Macro, meso	Burton, 2012, Cardona, 2005, Martínez, Vega-Garcia & Chuvieco, 2009, Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Agricultural area which became forest land (time span)*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Variation of land area that is used for agriculture (time span)*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Environmental Sustainability Index, ESI	Macro, meso	Cardona, 2005
	Soil degradation resulting from human activities	Macro, meso	Cardona, 2005
	Urban/forest interface area/density*	Meso	Martínez, Vega-Garcia & Chuvieco, 2009, Leone et al., 2003
	Wildland/urban interface area/density*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Leone et al., 2003
	Wildland/agriculture interface area/density*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Forest/cultivated land interface area/density*	Meso	Martínez, Vega-Garcia & Chuvieco, 2009; Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Leone et al., 2003
	Forest/pasture interface area/density*	Meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Forest/grassland interface area/density*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Leone et al., 2003
Vegetation fuel*	Surface covered by vegetation fuel (or organic matter)*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Jucker Riva et al., 2018
	Surface covered by shrubs*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Surface covered by grasslands*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Surface covered by wetlands*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017

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	Surface covered by coniferous forests*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Surface covered by broadleaves*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Biomass density (overall vegetation including dead material)*	Macro, meso	Jucker Riva et al., 2018
Infrastructure*	Hotels and motels per square kilometre	Macro, meso	Burton, 2012
	Schools (primary and secondary education) per square kilometre	Macro, meso	Burton, 2012
	Principal arterial km (roads density)*	Macro, meso	Burton, 2012; Martínez, Vega-Garcia & Chuvieco, 2009, Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Vallejo-Villalta et al., 2019, Jucker Riva et al., 2018, Oilveira et al., 2020, Leone et al., 2003
	Number of rail km/surface (railway density)*	Macro, meso	Burton, 2012, Martínez, Vega-Garcia & Chuvieco, 2009, Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Jucker Riva et al., 2018, Leone et al., 2003
	Number of power lines km/surface (power infrastructure density)*	Macro, meso	Vallejo-Villalta et al., 2019
	Waterways, drainage lines, ponds, dams*	Macro, meso	Jucker Riva et al., 2018
	Interface area between risk infrastructures (waste dumps, mines, quarries, areas under construction, roads more than 100 m wide) and forest areas	Meso	Martínez, Vega-Garcia & Chuvieco, 2009
Land Use and Land Coverage*	Percent land area that is non-developed/natural forest*	Macro, meso	Burton, 2012, Jucker Riva et al., 2018
	Percent land area which is private forest*	Macro, meso	Leone et al., 2003
	Percent land area which is public forest*	Macro, meso	Leone et al., 2003
	Reforested areas*	Macro, meso	Leone et al., 2003
	Percent land-cover that has not changed to urban areas*	Macro, meso	Burton, 2012, Leone et al., 2003

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	Denied requests to change to urban areas*	Macro, meso	Leone et al., 2003
	Surface covered by urban areas*	Macro, meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Leone et al., 2003
	Built-up surface*	Macro, meso	Vallejo-Villalta et al., 2019
	Soil covered by vegetation, litter, rocks and mosses*	Macro, meso	Jucker Riva et al., 2018
	Percent of land area with no land-cover/land-use change (time span)*	Macro, meso	Burton, 2012, Leone et al., 2003
	Percent of land area under protected status*	Macro, meso	Burton, 2012, Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Leone et al., 2003
	Land defined as "agriculture areas, but with significant areas of natural vegetation"*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Percentage of land under plantation/agroforestry*	Macro, meso	Jucker Riva et al., 2018
	Percentage of land under agriculture including plantation / forestry*	Macro, meso	ECLAC, 2011, Leone et al., 2003
	No. of agriculture farms / 10,000 sq. km	Macro, meso	ECLAC, 2011
	Percentage of land under agro-pastoralism/silvo-pastoralism/agro-silvopastoralism*	Macro, meso	Jucker Riva et al., 2018
	Percentage of total land area affected by mining / quarrying	Macro, meso	ECLAC, 2011, Jucker Riva et al. 2018, Leone et al., 2003
	Percentage of total land area occupied by military bases*	Macro, meso	Leone et al., 2003
	Percentage of surface set aside as reserves (including areas of the EU network "Nature 2000")*	Macro, meso	ECLAC, 2011; Martínez, Vega-Garcia & Chuvieco, 2009
	Water (rivers, lakes)*	Macro, meso	Jucker Riva et al., 2018
	Availability/protection of springs/water sources*	Macro, meso	Jucker Riva et al., 2018
	Over abstraction of water (for irrigation, industry etc.)*	Macro, meso	Jucker Riva et al., 2018
	Number of hunting licences*	Macro, meso	Leone et al., 2003
	Hunting reserve areas*	Macro, meso	Leone et al., 2003
Waste and pollution*	Total tonnage of imported toxic or hazardous wastes / 10,000 sq. km land area / year (average on time span)	Macro, meso	ECLAC, 2011

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	Tons pesticides produced, imported/10,000 sq. km area (average on time span)	Macro, meso	ECLAC, 2011
	Millions of litres of hydrocarbons used /10,000 sq. km land area / year (average on time span)	Macro, meso	ECLAC, 2011
	Toxic wastes disposed by high temperature incineration (average on time span)	Macro, meso	ECLAC, 2011
	Point of discharges (contamination of water)*	Macro, meso	Jucker Riva et al., 2018
	Disturbance of water cycle (infiltration/runoff)*	Macro, meso	Jucker Riva et al., 2018
	Uncontrolled rubbish dumps*	Macro, meso	Leone et al., 2003
Landscape patterns*	Landscape fragmentation index using a 7x7 kernel (average value)*	Meso	Martínez, Vega-Garcia & Chuvieco, 2009, Leone et al., 2003
	Landscape patch density (number of patches/territory)*	Meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Forest patch size (median value)*	Meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Agricultural land fragmentation: density of agricultural plots (¼number of plots/agriculture holding area in territory)*	Meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Continuity of vegetation canopy/cover	Meso	Jucker Riva et al., 2018
	Presence of different habitats (landscape heterogeneity)*	Meso	Jucker Riva et al., 2018
	Connectivity between healthy areas*	Meso	Jucker Riva et al., 2018
Land management*	Deforestation/removal of natural vegetation (including forest fires)*	Meso	Jucker Riva et al., 2018
	Grazing*	Meso	Jucker Riva et al., 2018
	Cropping activities*	Meso	Jucker Riva et al., 2018
	Forest area managed by Forest administration*	Macro, meso	Leone et al., 2003
Residential property*	Average Household Size	Macro, meso	Baum et al., 2008
	Percentage of constructions of strong resistance	Macro, meso	Eidsvig et al., 2011
	Percentage of constructions of medium resistance	Macro, meso	Eidsvig et al., 2011
	Percentage of constructions of weak resistance	Macro, meso	Eidsvig et al., 2011
	Single storey accommodation	Macro, meso	ENSURE, 2009, Tapsell, 2005
	Mobile housing	Macro, meso	ENSURE, 2009, Tapsell, 2005
	Percentage of vacant housing*	Macro, meso	Oilveira et al., 2020

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	Number of rooms	Macro, meso	ENSURE, 2009, Tapsell, 2005
Urbanization and human pressure	Density of single family detached homes/isolated buildings*	Macro, meso	Burton, 2012, Oilveira et al., 2020
	Percentage of ancient buildings (built before a specific time)*	Macro, meso	Oilveira et al., 2020
	Percentage of buildings made of stone and adobe*	Macro, meso	Oilveira et al., 2020
	Density of all building infrastructure*	Macro, meso	Burton, 2012; Martínez, Vega-Garcia & Chuvieco, 2009, Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Oilveira et al., 2020, Jucker Riva et al., 2018
	Population average annual growth rate*	Macro	Cardona, 2005, Martínez, Vega-Garcia & Chuvieco, 2009, Leone et al., 2003
	Percentage of the population living in high intensity urban areas	Macro, meso	Burton, 2012
	Percentage of the population living in disseminate housing*	Macro, meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Percentage of population in rural areas*	Macro, meso	Leone et al., 2003
	Population density*	Macro, meso	Eidsvig et al., 2011, Cardona, 2005, Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Oilveira et al., 2020, Leone et al., 2003
	Urban average annual growth rate (%)*	Macro	Cardona, 2005, Jucker Riva et al., 2018
	Average distance of high risk areas from roads*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Leone et al., 2003
	Average distance of high risk areas from settlements*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017, Leone et al., 2003
	Average distance of high risk areas from railroads*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia, 2017
	Average distance of high risk areas from recreational areas*	Meso	Costafreda-Aumedes, Comas & Vega-Garcia,

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			2017, Leone et al., 2003
	Average distance of high risk areas from electric lines*	Meso	Leone et al., 2003
	Force of attraction of population centre or settlement*	Meso	Martínez, Vega-Garcia & Chuvieco, 2009
	Touristic arrivals*	Macro, meso	Leone et al., 2003

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Assessment of Vulnerability Indicators and Proxies

The following tables aim to illustrate the results of the ReSVI calculation at Pilot Sites level.

Social Dimension

Social Dimension Indicators and Proxies

Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
Age*	Percentage of residents aged 65 years or above*	-	0	1	1	-
	Median age	-	0	1	0.5	-
	Percentage of population below 5	-	0	1	1	-
	Percentage of young people (< 20 yo)*	-	0	0.5	0.5	-
	Percentage of population aged below 15*	-	0	1	0.5	-
	Percentage of population aged over 75*	-	0	1	1	-
	Age dependency rate*	-	0	0.5	1	-
Communication services*	Internet, television, radio, and telecommunications broadcasters per 1,000 inhabitants	-	0	0.5	0.5	-
	Percentage of area with mobile phone coverage*	-	0	0.5	0.5	-
	Percentage of area with excellent or good ADSL service*	-	0	0	0	-
Community Capital*	Religious organizations per 1,000 inhabitants	-	0	0	0	-
	Professional, scientific, and technical services per 1,000 inhabitants	-	0	0	0.5	-
	Research and development firms per 1,000 inhabitants	-	0	0	0.5	-
	Social advocacy organizations per 1,000 inhabitants	-	0	0	0.5	-
	Arts, entertainment, and recreation centres per 1,000 inhabitants	-	0	0	0	-
	Civic organisations per 1,000 inhabitants	-	0	0	0	-
	Historical heritage sites per square kilometre	-	0	0.5	0	-
	Percentage of population with high generalised trust*	-	0	0	0	-
	Percentage of population with life satisfaction scale 70 or above*	-	0	0	0	-
	Offences against persons per 100,000 inhabitants*	-	0	0	0	-
	Offences against property per 100,000 inhabitants*	-	0.5	0	0	-

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
	Percentage of people undertaking voluntary work*	-	0	0.5	0	-
Family structure*	Average number of people per bedroom	-	0	0	0	-
	Percentage of people separated or divorced	-	0	0	0	-
	Percentage of people married	-	0	0	0	-
	Percentage of people who are widowed	-	0	0	0	-
	Percentage of single parent families*	-	0.5	0	0.5	-
	Percentage of lone persons households*	-	0.5	0.5	1	-
	Percentage of households with children*	-	0.5	0.5	1	-
Gender*	Percentage of women*	-	0	0	0.5	-
	Percentage of men	-	0	0	0.5	-
	Gender-related Development Index, GDI	-	0	0	0	-
Migrations, Race and Ethnicity*	Percentage of the population that is not an ethnic minority	-	0	0	0	-
	Percentage of persons born abroad who arrived in the past five years	-	0.5	0	0	-
	Percentage of the population is not familiar with majority language and culture	-	0.5	1	0	-
	Migration effectiveness*	-	0	0.5	0	-
Social dependence	Social assistance programs per 1,000 inhabitants	-	0.5	0.5	1	-
Special needs populations	Percentage of the population that is not institutionalized or infirmed	-	0	0	0.5	-
	Childcare programs per 1,000 inhabitants	-	0	0	0.5	-
	Percentage of residents who require assistance with daily tasks	-	0.5	1	1	-
Wealth and Socio-economic status*	Percentage of the population with vehicle access*	-	0.5	0.5	0.5	-
	Percentage of the population with telephone access	-	0	0.5	1	-
	Human Development Index	-	0	0	0.5	-
	Human Poverty Index, HPI	-	0	0	0.5	-
	GINI coefficient	-	0	0	0.5	-
	Business and professional organizations per 1,000 inhabitants	-	0	0	0	-

Economic Dimension

Economic Dimension Indicators and Proxies

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
Wealth and Socio-economic status*	Percentage of home ownership*	-	0	0.5	0	-
	Land tenure*	-	0	0.5	0	-
	GDP per capita*	-	0	0	0.5	-
	Electricity consumption kilowatt hours / capita/ year	-	0	0	0	-
	Per capita household income	-	0	0	0.5	-
	Median individual income*	-	0	0	0.5	-
	Annual increase in food prices (%)	-	0	0	0	-
	Energy prices*	-	0	0	0	-
	Median monthly mortgage repayment*	-	0	0	0	-
Business structure	Ratio of large to small businesses	-	0	0	0	-
	Retail centres per 1,000 inhabitants	-	0	0	0	-
	Commercial establishments per 1,000 inhabitants	-	0	0	0	-
	Mean sales volume of businesses	-	0	0	0	-
	Lending institutions per 1,000 inhabitants	-	0	0	0	-
	Percentage of commercial establishments outside of high wildfire hazard zones	-	0	0	0	-
	Density of commercial infrastructure	-	0	0	0	-
	Imports and exports of goods and services as a Percentage of GDP	-	0	0	0	-
Primary sector*	Share of agriculture in total GDP growth (annual %)	-	1	0	0	-
	Percentage of population occupied in the primary sector*	-	1	0.5	0.5	-
	Energy consumption in agriculture*	-	0	0	0	-
	Variation of number of owners of agrarian holdings (time span)*	-	0	0.5	0.5	-
	Percentage of owners of agrarian holdings with >55 years*	-	0.5	0.5	0.5	-
	Density of agricultural machinery (include all kind of tractors, combine harvesters, binders, millings machines, hoe machines, seed drills, etc.)*	-	0	0.5	0.5	-
	Livestock density in extensive regime (not in stables)*	-	0.5	0.5	0.5	-
	Livestock density*	-	0.5	0.5	0.5	-
	Number of pasture licences*	-	0	0.5	0.5	-
	Market prices of goods produced from the land (e.g. wood, cheese or meat, honey, energy etc.)*	-	0.5	0.5	0	-
	Average market price of wood*	-	0.5	0.5	0	-
	Yearly price of wood variation*	-	0.5	0.5	0	-

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
	Forest commercial value*	-	1	0.5	0.5	-
	Forest area with low potential forest productivity*	-	0	0.5	1	-
	% employed in traditional activities in wildland/rural areas (cattle grazing, firewood extraction, resin and cork production)*	-	0	0.5	0.5	-
Capitals	Social expenditures on pensions, health and education as a Percentage of GDP	-	0	0	0.5	-
	Capital stock in millions of € per thousand square kilometres	-	0	0	0	-
	Gross domestic fixed investment as a Percentage of GDP	-	0	0	0	-
	Debt service burden as a percentage of GDP	-	0	0	0	-

Institutional Dimension

Institutional Dimension Indicators and Proxies

Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
Emergency response*	Existence of an organisation of emergency response, with coordination authority	-	1	1	1	-
	Fire and emergency services per 1,000 inhabitants*	-	1	1	1	-
	Police services per 1,000 inhabitants*	-	1	0.5	0.5	-
	Ambulance officers and paramedics per 1,000 inhabitants*	-	1	0.5	0.5	-
	Temporary shelters per 1,000 inhabitants	-	0.5	1	0	-
	Percentage of fire, police, emergency relief services, and temporary shelters outside of hazard zones	-	1	0.5	0	-
	Early warning systems used in coordination with emergency response procedures	-	1	1	0.5	-
	Number of days of work in fire control activity of seasonal fire fighters*	-	1	1	0.5	-
	Shelters per 1,000 inhabitants*	-	0.5	1	0	-
Risk Financing	Infrastructure and housing insurance as a Percentage of GDP	-	0	0.5	0	-
	Percentage of the population with Citizen Corps program participation	-	0.5	0.5	0	-
Risk Mitigation*	Percentage of the population covered by a recent hazard mitigation plan	-	1	1	0	-

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
	Protection and management of forest land*	-	0	1	1	-
	Percentage of forest surface with less management, control and planning over time[37]*	-	1	1	1	-
Risk Awareness	Hazard maps available	-	1	1	1	-
	Assessment of direct impacts to exposed populations	-	1	1	1	-
	Levels of risk awareness and preparedness	-	1	1	1	-
	Previous wildfire hazard experience	-	1	1	1	-
Regulations*	Guidelines in place for all constructions and land-use activities to ensure minimal risk to exposed population	-	1	1	0.5	-
	Regulation of construction and land use*	-	1	1	1	-
	Percentage of development projects accompanied by Environmental Impact Assessment	-	0	1	0	-
	Number of expropriation expedients or actions*	-	0	0	0	-
Incentives*	Subsidies for land use activity (agriculture, farming, tourism and others)*	-	1	0.5	1	-
	Subsidies for land management or nature conservation*	-	1	0.5	1	-
Governance*	Voice and accountability	-	0	0	0	-
	Civil liberties	-	0	0	0	-
	Political rights	-	0	0	0	-
	Access to decision-making	-	0	0	0	-
	Trust in authorities	-	0	0	0	-
	Governance Index (Kaufmann)	-	0	0	0	-
	Cooperation and community organisation*	-	0	0	1	-

Human Capital Dimension

Human Capital Dimension Indicators and Proxies

Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
Educational Level*	Adult education and skills-training programs per 1,000 inhabitants	-	0.5	0.5	0.5	-

[37] In the Spanish case: private forest land, land belonging to local authorities with free use, consortiums and neighbouring forest common land.

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
	Percentage of the eligible population (over 18 years of age) have attended, or are attending, a post-secondary education	-	0.5	0	0	-
	Percentage population with elementary school level*	-	0.5	0.5	0.5	-
	Percentage population with secondary school level*	-	0.5	0.5	0	-
	Percentage population with higher educational level*	-	0.5	0	0	-
	Literacy rate*	-	0	0.5	0	-
	Literacy rate (% of population over 15)	-	0	0.5	0	-
	Literacy rate (% of 15-24 year olds)	-	0	0.5	0	-
	Literacy ratio (female to male)	-	0	0	0	-
Health Services*	Percent of the population without a disability	-	0	1	1	-
	Psychosocial support facilities per 1,000 inhabitants	-	0	0.5	0	-
	Health services per 1,000 inhabitants	-	0.5	0.5	0.5	-
	Hospital beds per 1,000 people*	-	0.5	0	0	-
	Number of doctors and medical professionals per 1,000 inhabitants*	-	0.5	0	0	-
	Psychologists per 1,000 inhabitants*	-	0	0.5	0	-
	Population with access to sanitation (%)	-	0	0	0	-
	Life expectancy at birth	-	0	0	0	-
	Maternal mortality per 100 thousand	-	0	0	0	-
Occupation*	Percentage of population dependent on the land for primary source of income	-	0.5	1	1	-
	Ratio of skilled and unskilled workers	-	0	0	1	-
	Percentage of the population employed as managers and professionals*	-	0	0	0	-
	Percentage of the population that is employed*	-	0	0.5	0	-
	Male labour force participation rate	-	0	0	0	-
	Female labour force participation rate	-	0	0	0	-
	Percentage of unemployment from the total labour force*	-	0	0.5	0	-
	Percentage of the population not employed in primary industry	-	0	0	0	-

Environmental Dimension

Environmental Dimension Indicators and Proxies

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
Physiography*	Elevation (average)*	-	0.5	1	0	-
	Aspect*	-	1	1	0	-
	Slope (average)*	-	1	1	0	-
	Topographic roughness*	-	1	1	0.5	-
	Soil erosion*	-	0.5	0	0	-
	Soil moisture*	-	1	0	0.5	-
	Soil drainage/infiltration*	-	1	0	0	-
	Surface runoff*	-	1	0	0	-
Biodiversity (fauna)*	No. of species which have become extinct this century / 10,000 sq. km land	-	0	0	0	-
	No. threatened, endangered species/10,000 sq. km land	-	0	1	0.5	-
	No. introduced terrestrial species/10,000 sq. km land (over last 100 years)	-	0	0.5	0	-
	No. of endemic species/10,000 sq. km land	-	0	0.5	0.5	-
	Soil fauna*	-	0	0.5	0	-
	Birds*	-	0	0.5	0	-
	Wild grazers*	-	0.5	0.5	0.5	-
	Domestic grazers*	-	0	1	1	-
	Predators*	-	0.5	0.5	0.5	-
Biodiversity (flora)*	Presence of a mixture of grasses, shrubs and trees (complex vegetation structure)*	-	1	1	0.5	-
	Number of present species (vegetation diversity)*	-	1	0.5	0	-
	Presence of a specific plant or group (e.g. resprouters, palatables)*	-	1	0.5	1	-
	Presence of alien/dangerous species*	-	1	0.5	0	-
Environmental Systems*	Percent land area that consists of windbreaks and environmental plantings	-	1	0.5	1	-
	Percent land area that is developed open space	-	0	0	1	-
	Percent land area that is arable cultivated land*	-	1	1	1	-
	Agricultural area which became forest land (time span)*	-	1	0.5	0.5	-
	Variation of land area that is used for agriculture (time span)*	-	0	0.5	0.5	-
	Environmental Sustainability Index, ESI	-	0	0.5	0	-
	Soil degradation resulting from human activities	-	0	0.5	0	-
	Urban/forest interface area/density*	-	1	1	0	-

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
	Wildland/urban interface area/density*	-	1	1	1	-
	Wildland/agriculture interface area/density*	-	1	1	0	-
	Forest/cultivated land interface area/density*	-	1	0.5	0	-
	Forest/pasture interface area/density*	-	1	0.5	0	-
	Forest/grassland interface area/density*	-	1	0.5	0	-
Vegetation fuel*	Surface covered by vegetation fuel (or organic matter)*	-	1	1	0	-
	Surface covered by shrubs*	-	1	1	0.5	-
	Surface covered by grasslands*	-	1	1	0.5	-
	Surface covered by wetlands*	-	1	1	0.5	-
	Surface covered by coniferous forests*	-	1	1	0.5	-
	Surface covered by broadleaves*	-	1	1	0.5	-
	Biomass density (overall vegetation including dead material)*	-	1	1	1	-
Infrastructure*	Hotels and motels per square kilometre	-	0	1	0	-
	Schools (primary and secondary education) per square kilometre	-	0	1	0	-
	Principal arterial km (roads density)*	-	1	1	1	-
	Number of rail km/surface (railway density)*	-	1	1	0	-
	Number of power lines km/surface (power infrastructure density)*	-	1	1	0.5	-
	Waterways, drainage lines, ponds, dams*	-	0.5	1	0	-
	Interface area between risk infrastructures (waste dumps, mines, quarries, areas under construction, roads more than 100 m wide) and forest areas	-	0.5	1	0	-
Land Use and Land Coverage*	Percent land area that is non-developed/natural forest*	-	1	0.5	0.5	-
	Percent land area which is private forest*	-	1	1	0.5	-
	Percent land area which is public forest*	-	1	1	0	-
	Reforested areas*	-	1	0.5	0.5	-
	Percent land-cover that has not changed to urban areas*	-	0.5	0	0.5	-
	Denied requests to change to urban areas*	-	0	0	0	-
	Surface covered by urban areas*	-	0	0.5	0	-

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
	Built-up surface*	-	0	1	0	-
	Soil covered by vegetation, litter, rocks and mosses*	-	0.5	1	0	-
	Percent of land area with no land-cover/land-use change (time span)*	-	0	1	0	-
	Percent of land area under protected status*	-	1	1	1	-
	Land defined as "agriculture areas, but with significant areas of natural vegetation"*	-	0.5	1	0.5	-
	Percentage of land under plantation/Agroforestry*	-	1	0.5	0.5	-
	Percentage of land under agriculture including plantation / forestry*	-	1	1	0.5	-
	No. of agriculture farms / 10,000 sq. km	-	0.5	0.5	0.5	-
	Percentage of land under agro-pastoralism/silvo-pastoralism/agro-silvopastoralism*	-	0	0.5	1	-
	Percentage of total land area affected by mining / quarrying	-	0	0	0	-
	Percentage of total land area occupied by military bases*	-	1	0	0	-
	Percentage of surface set aside as reserves (including areas of the EU network "Nature 2000")*	-	1	1	1	-
	Water (rivers, lakes)*	-	0.5	1	0.5	-
	Availability/protection of springs/water sources*	-	1	1	0	-
	Over abstraction of water (for irrigation, industry etc.)*	-	0.5	0.5	0	-
	Number of hunting licences*	-	0	0	0	-
	Hunting reserve areas*	-	0	0.5	0	-
Waste and pollution*	Total tonnage of imported toxic or hazardous wastes / 10,000 sq. km land area / year (average on time span)	-	0	0	0	-
	Tons pesticides produced, imported/10,000 sq. km area (average on time span)	-	0	0	0	-
	Millions of litres of hydrocarbons used /10,000 sq. km land area / year (average on time span)	-	0	0	0	-
	Toxic wastes disposed by high temperature incineration (average on time span)	-	0	0	0	-
	Point of discharges (contamination of water)*	-	0	0	0	-

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
	Disturbance of water cycle (infiltration/runoff)*	-	0	0.5	0	-
	Uncontrolled rubbish dumps*	-	0	0.5	0	-
Landscape patterns*	Landscape fragmentation index using a 7x7 kernel (average value)*	-	1	0.5	0.5	-
	Landscape patch density (number of patches/territory)*	-	1	1	0.5	-
	Forest patch size (median value)*	-	1	0.5	1	-
	Agricultural land fragmentation: density of agricultural plots (¼number of plots/agriculture holding area in territory)*	-	1	0.5	0.5	-
	Continuity of vegetation canopy/cover	-	1	1	0.5	-
	Presence of different habitats (landscape heterogeneity)*	-	1	0.5	0	-
	Connectivity between healthy areas*	-	1	0.5	0	-
Land management*	Deforestation/removal of natural vegetation (including forest fires)*	-	1	0.5	0.5	-
	Grazing*	-	0.5	1	1	-
	Cropping activities*	-	0.5	1	0.5	-
	Forest area managed by Forest administration*	-	1	1	1	-
Residential property*	Average Household Size	-	0	0.5	0.5	-
	Percentage of constructions of strong resistance	-	0	1	1	-
	Percentage of constructions of medium resistance	-	0	1	0.5	-
	Percentage of constructions of weak resistance	-	0	1	1	-
	Single storey accommodation	-	0	0.5	0	-
	Mobile housing	-	0	0.5	1	-
	Percentage of vacant housing*	-	0	1	0.5	-
	Number of rooms	-	0	0	0	-
Urbanization and human pressure	Density of single family detached homes/isolated buildings*	-	0.5	0.5	0.5	-
	Percentage of ancient buildings (built before a specific time)*	-	0	1	0	-
	Percentage of buildings made of stone and adobe*	-	0	1	1	-
	Density of all building infrastructure*	-	0.5	1	1	-
	Population average annual growth rate*	-	0	0.5	0.5	-
	Percentage of the population living in high intensity urban areas	-	0	0.5	0.5	-
	Percentage of the population living in disseminate housing*	-	0	1	0.5	-

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Indicator	Proxy	PS1	PS2	PS3	PS4	PS5
	Percentage of population in rural areas*	-	0.5	1	0.5	-
	Population density*	-	0.5	0.5	1	-
	Urban average annual growth rate (%)*	-	0	0	0.5	-
	Average distance of high risk areas from roads*	-	1	1	0.5	-
	Average distance of high risk areas from settlements*	-	1	1	0.5	-
	Average distance of high risk areas from railroads*	-	1	1	0	-
	Average distance of high risk areas from recreational areas*	-	1	1	0.5	-
	Average distance of high risk areas from electric lines*	-	1	1	0	-
	Force of attraction of population centre or settlement*	-	0	0.5	0	-
	Touristic arrivals*	-	0	0.5	0.5	-

Implementation of the Societal Vulnerability Index in PS3 – Mediterranean Portugal

The following tables aim to illustrate the results for the societal vulnerability analysis in PS3 – Mediterranean Portugal

Additional proxies proposed during the assessment

Additional proxies suggested by ADAI

Dimension	Indicator	Proxy	Note
Human Capital	Health Services	Adult intensive care beds per 100,000 inhabitants	-
		Practising nurses per 1,000 population	-
Environmental	Forest Fire Risk Map	Elevation (Digital Elevation Model - DEM)	-
		Aspect (Terrain orientation)	-
		Terrain slope	
		Topographic roughness	
		Proximity to Roads spatial distribution	
		Land-use/occupation	
		Water deficit spatial distribution (Annual average)	
		Rainfall spatial distribution (Annual average)	
		Temperature spatial distribution (Annual average)	
		Evapotranspiration	-

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Dimension	Indicator	Proxy	Note
Environmental	Physiography	-	These points (5.1.5 to 5.1.8) are more related to soil management, recovery of degraded areas, and hydrology. I suggest another topic: The evaluation and records of abandoned rural properties. When there is no vegetation management, fire risks are imminent. Identifying and locating these properties can be significant in the wildfire context, especially those close to cities.
Environmental	CAR-PT		To prevent the fire risk, we can develop a Rural Environmental Registry of Portugal (CAR-PT) platform. The national electronic public record is mandatory for all rural properties. In Brazil, the Web platform was created by Law nº 12.651/2012, within the scope of the National Environmental Information System - SINIMA, and regulated by Normative Instruction MMA nº 2, of May 5, 2014. The CAR aims to integrate environmental information from rural properties and possessions referring to preservation areas, cropping activities, forest areas, and other forms of native vegetation, and consolidated areas, composing a database for control, monitoring, and environmental and economic planning for combating wildfire. Personal information, such as the owner's name and NIF, remains confidential. This module allows, through an easy and very friendly interface, to have access to property data from all over the country. Anyone with internet access will be able to consult and even download Excel and Shapefile data with the georeferenced data of the properties registered in each municipality.

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PS3 RESVI Calculation – NUTS-3 Coimbra

RESVI Index – NUTS-3 Coimbra

Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Social	Age	0.39	0.44	Percentage of residents aged 65 years or above	0.37	0.37
				Median age	0.43	0.43
				Percentage of population aged below 15	0.57	0.57
				Age dependency rate	0.20	0.40
	Communication services	N/A	N/A	Internet coverage	N/A	N/A
	Family structure	N/A	N/A	Percentage of single parent families	N/A	N/A
				Percentage of lone persons households	N/A	N/A
				Percentage of households with children	N/A	N/A
	Migration, race and ethnicity	0.22	0.22	Percentage of the population is not familiar with majority language and culture	0.22	0.22
Total Social					**0.30**	**0.33**
Economic	Wealth and Socio-economic status	0.14	0.67	Percentage of home ownership	0.28	0.56
				Electricity consumption kilowatt hours / capita/ year	0.00	0.78
	Business structure	0.00	0.37	Density of commercial infrastructure	0.00	0.37
	Primary sector	0.15	0.29	Percentage of population occupied in the primary sector	0.29	0.59
				Variation of number of owners of agrarian holdings (time span) (2013-2016)	N/A	N/A
				Forest area with low potential forest productivity	0.00	0.00
Total Economic					**0.10**	**0.44**

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Institutional	Emergency response	N/A	N/A	Ambulance officers and paramedics per 1,000 inhabitants	N/A	N/A
Total Institutional					**N/A**	**N/A**
Human Capital	Educational level	-	-	Adult education and skills-training programs per 1,000 inhabitants	N/A	N/A
				Percentage of the eligible population (over 18 years of age) have attended, or are attending, a post-secondary education	N/A	N/A
				Percentage population with elementary school level	N/A	N/A
				Percentage population with secondary school level	N/A	N/A
				Percentage population with higher educational level	N/A	N/A
	Health Services	0.00	0.46	Population with access to sanitation (%) (2020)	0.00	0.46
	Occupation	0.09	0.40	Percentage of population dependent on the land for primary source of income	0.12	0.12
				Ratio of skilled and unskilled workers	N/A	N/A
				Male labour force participation rate	0.00	0.68
				Female labour force participation rate	0.00	0.28
				Percentage of unemployment from the total labour force	0.25	0.50
				Percentage of the population not	N/A	N/A

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
				employed in primary industry		
Total Human Capital					**0.05**	**0.43**
Environmental	Physiography	0.29	0.29	Elevation (average)	0.29	0.29
	Environmental Services	N/A	N/A	Percent land area that is arable cultivated land	N/A	N/A
	Vegetation Fuel	0.00	0.00	Surface covered by wetlands	0.00	0.00
	Land use and land coverage	0.27	0.27	Percentage of surface set aside as reserves (including areas of the EU network "Nature 2000")	0.27	0.27
Total Environmental					**0.19**	**0.19**

PS3 RESVI Calculation – NUTS-3 Leiria

RESVI Index – NUTS-3 Leiria

Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Social	Age	0.37	0.41	Percentage of residents aged 65 years or above	0.37	0.37
				Median age	0.35	0.35
				Percentage of population aged below 15	0.57	0.57
				Age dependency rate	0.17	0.34
	Communication services	N/A	N/A	Internet coverage	N/A	N/A
	Family structure	N/A	N/A	Percentage of single parent families	N/A	N/A
				Percentage of lone persons households	N/A	N/A
				Percentage of households with children	N/A	N/A
	Migration, race and ethnicity	0.94	0.94	Percentage of the population is not familiar with majority language and culture	0.94	0.94
Total Social					**0.65**	**0.69**

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Economic	Wealth and Socio-economic status	0.14	0.63	Percentage of home ownership	0.27	0.55
				Electricity consumption kilowatt hours / capita/ year	0.00	0.72
	Business structure	0.00	0.29	Density of commercial infrastructure	0.00	0.29
	Primary sector	0.41	0.82	Percentage of population occupied in the primary sector	0.32	0.64
				Variation of number of owners of agrarian holdings (time span) (2013-2016)	N/A	N/A
				Forest area with low potential forest productivity	0.50	1.00
Total Economic					**0.18**	**0.58**
Institutional	Emergency response	N/A	N/A	Ambulance officers and paramedics per 1,000 inhabitants	N/A	N/A
Total Institutional					**N/A**	**N/A**
Human Capital	Educational level	N/A	N/A	Adult education and skills-training programs per 1,000 inhabitants	N/A	N/A
				Percentage of the eligible population (over 18 years of age) have attended, or are attending, a post-secondary education	N/A	N/A
				Percentage population with elementary school level	N/A	N/A
				Percentage population with secondary school level	N/A	N/A
				Percentage population with higher educational level	N/A	N/A

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
	Health Services	0.00	0.44	Population with access to sanitation (%) (2020)	0.00	0.44
	Occupation	0.15	0.46	Percentage of population dependent on the land for primary source of income	0.41	0.41
				Ratio of skilled and unskilled workers	N/A	N/A
				Male labour force participation rate	0.00	0.55
				Female labour force participation rate	0.00	0.46
				Percentage of unemployment from the total labour force	0.21	0.42
				Percentage of the population not employed in primary industry	N/A	N/A
Total Human Capital					**0.08**	**0.45**
Environmental	Physiography	0.16	0.16	Elevation (average)	0.16	0.16
	Environmental Services	N/A	N/A	Percent land area that is arable cultivated land	N/A	N/A
	Vegetation Fuel	0.73	0.73	Surface covered by wetlands	0.73	0.73
	Land use and land coverage	0.23	0.23	Percentage of surface set aside as reserves (including areas of the EU network "Nature 2000")	0.23	0.23
Total Environmental					**0.37**	**0.37**

PS3 RESVI Calculation – Municipality Lousã

RESVI Index – Municipality Lousã

Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Social	Age	0.35	0.42	Percentage of residents aged 65 years or above	0.32	0.32

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
				Median age	0.31	0.31
				Percentage of population aged below 15	0.61	0.61
				Age dependency rate	0.14	0.29
	Communication services	N/A	N/A	Internet coverage	N/A	N/A
	Family structure	N/A	N/A	Percentage of single parent families	N/A	N/A
				Percentage of lone persons households	N/A	N/A
				Percentage of households with children	N/A	N/A
	Migration, race and ethnicity	N/A	N/A	Percentage of the population is not familiar with majority language and culture	N/A	N/A
Total Social					**0,42**	**0.42**
Economic	Wealth and Socio-economic status	0.14	0.50	Percentage of home ownership	0.28	0.56
				Electricity consumption kilowatt hours / capita/ year	0.00	0.45
	Business structure	0.00	0.34	Density of commercial infrastructure	0.00	0.34
	Primary sector	0.27	0.54	Percentage of population occupied in the primary sector	0.27	0.54
				Variation of number of owners of agrarian holdings (time span) (2013-2016)	N/A	N/A
				Forest area with low potential forest productivity	N/A	N/A
Total Economic					**0,51**	**0.46**
Institutional	Emergency response	0.38	0.76	Ambulance officers and paramedics per 1,000 inhabitants	0.38	0.76
Total Institutional					**0,63**	**0.76**
Human Capital	Educational level	N/A	N/A	Adult education and skills-training	N/A	N/A

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
				programs per 1,000 inhabitants		
				Percentage of the eligible population (over 18 years of age) have attended, or are attending, a post-secondary education	N/A	N/A
				Percentage population with elementary school level	N/A	N/A
				Percentage population with secondary school level	N/A	N/A
				Percentage population with higher educational level	N/A	N/A
	Health Services	0.00	0.42	Population with access to sanitation (%) (2020)	0.00	0.42
	Occupation	0.10	0.51	Percentage of population dependent on the land for primary source of income	N/A	N/A
				Ratio of skilled and unskilled workers	N/A	N/A
				Male labour force participation rate	0.00	0.66
				Female labour force participation rate	0.00	0.30
				Percentage of unemployment from the total labour force	0.29	0.57
				Percentage of the population not employed in primary industry	N/A	N/A
Total Human Capital					**0.05**	**0.47**
	Physiography	N/A	N/A	Elevation (average)	N/A	N/A

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Environmental	Environmental Services	N/A	N/A	Percent land area that is arable cultivated land	N/A	N/A
	Vegetation Fuel	N/A	N/A	Surface covered by wetlands	N/A	N/A
	Land use and land coverage	N/A	N/A	Percentage of surface set aside as reserves (including areas of the EU network "Nature 2000")	N/A	N/A
Total Environmental					**N/A**	**N/A**

PS3 RESVI Calculation – Municipality Castanheira de Pêra

RESVI Index – Municipality Castanheira de Pêra

Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Social	Age	0.54	0.63	Percentage of residents aged 65 years or above	0.73	0.73
				Median age	0.70	0.70
				Percentage of population aged below 15	0.40	0.40
				Age dependency rate	0.35	0.70
	Communication services	N/A	N/A	Internet coverage	N/A	N/A
	Family structure	N/A	N/A	Percentage of single parent families	N/A	N/A
				Percentage of lone persons households	N/A	N/A
				Percentage of households with children	N/A	N/A
	Migration, race and ethnicity	N/A	N/A	Percentage of the population is not familiar with majority language and culture	N/A	N/A
Total Social					**0.54**	**0.63**
Economic	Wealth and Socio-economic status	0.14	0.47	Percentage of home ownership	0.29	0.57

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
				Electricity consumption kilowatt hours / capita/ year	0.00	0.37
	Business structure	0.00	0.64	Density of commercial infrastructure	0.00	0.64
	Primary sector	0.19	0.38	Percentage of population occupied in the primary sector	0.19	0.38
				Variation of number of owners of agrarian holdings (time span) (2013-2016)	N/A	N/A
				Forest area with low potential forest productivity	N/A	N/A
Total Economic					**0.11**	**0.50**
Institutional	Emergency response	N/A	N/A	Ambulance officers and paramedics per 1,000 inhabitants	N/A	N/A
Total Institutional					**N/A**	**N/A**
Human Capital	Educational level	N/A	N/A	Adult education and skills-training programs per 1,000 inhabitants	N/A	N/A
				Percentage of the eligible population (over 18 years of age) have attended, or are attending, a post-secondary education	N/A	N/A
				Percentage population with elementary school level	N/A	N/A
				Percentage population with secondary school level	N/A	N/A
				Percentage population with higher educational level	N/A	N/A

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
	Health Services	0.00	0.42	Population with access to sanitation (%) (2020)	0.00	0.42
	Occupation	0.11	0.55	Percentage of population dependent on the land for primary source of income	N/A	N/A
				Ratio of skilled and unskilled workers	N/A	N/A
				Male labour force participation rate	0.00	0.59
				Female labour force participation rate	0.00	0.40
				Percentage of unemployment from the total labour force	0.34	0.67
				Percentage of the population not employed in primary industry	N/A	N/A
Total Human Capital					**0.06**	**0.49**
Environmental	Physiography	N/A	N/A	Elevation (average)	N/A	N/A
	Environmental Services	N/A	N/A	Percent land area that is arable cultivated land	N/A	N/A
	Vegetation Fuel	N/A	N/A	Surface covered by wetlands	N/A	N/A
	Land use and land coverage	N/A	N/A	Percentage of surface set aside as reserves (including areas of the EU network "Nature 2000")	N/A	N/A
Total Environmental					**N/A**	**N/A**

PS3 RESVI Calculation – Municipality Figueiró dos Vinhos

RESVI Index – Municipality Figueiró dos Vinhos

Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Social	Age	0.51	0.59	Percentage of residents aged 65 years or above	0.65	0.65

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
				Median age	0.63	0.63
				Percentage of population aged below 15	0.44	0.44
				Age dependency rate	0.31	0.63
	Communication services	N/A	N/A	Internet coverage	N/A	N/A
	Family structure	N/A	N/A	Percentage of single parent families	N/A	N/A
				Percentage of lone persons households	N/A	N/A
				Percentage of households with children	N/A	N/A
	Migration, race and ethnicity	N/A	N/A	Percentage of the population is not familiar with majority language and culture	N/A	N/A
Total Social					**0.51**	**0.59**
Economic	Wealth and Socio-economic status	0.14	0.43	Percentage of home ownership	0.27	0.54
				Electricity consumption kilowatt hours / capita/ year	0.00	0.32
	Business structure	0.00	0.65	Density of commercial infrastructure	0.00	0.65
	Primary sector	0.23	0.46	Percentage of population occupied in the primary sector	0.23	0.46
				Variation of number of owners of agrarian holdings (time span) (2013-2016)	N/A	N/A
				Forest area with low potential forest productivity	N/A	N/A
Total Economic					**0.12**	**0.51**
Institutional	Emergency response	N/A	N/A	Ambulance officers and paramedics per 1,000 inhabitants	N/A	N/A
Total Institutional					**N/A**	**N/A**
Human Capital	Educational level	N/A	N/A	Adult education and skills-training	N/A	N/A

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
				programs per 1,000 inhabitants		
				Percentage of the eligible population (over 18 years of age) have attended, or are attending, a post-secondary education	N/A	N/A
				Percentage population with elementary school level	N/A	N/A
				Percentage population with secondary school level	N/A	N/A
				Percentage population with higher educational level	N/A	N/A
	Health Services	0.00	0.44	Population with access to sanitation (%) (2020)	0.00	0.44
	Occupation	0.09	0.54	Percentage of population dependent on the land for primary source of income	N/A	N/A
				Ratio of skilled and unskilled workers	N/A	N/A
				Male labour force participation rate	0.00	0.41
				Female labour force participation rate	0.00	0.65
				Percentage of unemployment from the total labour force	0.28	0.55
				Percentage of the population not employed in primary industry	N/A	N/A
Total Human Capital					**0.05**	**0.49**
	Physiography	N/A	N/A	Elevation (average)	N/A	N/A

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Environmental	Environmental Services	N/A	N/A	Percent land area that is arable cultivated land	N/A	N/A
	Vegetation Fuel	N/A	N/A	Surface covered by wetlands	N/A	N/A
	Land use and land coverage	N/A	N/A	Percentage of surface set aside as reserves (including areas of the EU network "Nature 2000")	N/A	N/A
Total Environmental					**N/A**	**N/A**

Implementation of the Societal Vulnerability Index in PS4 – Mediterranean Spain

The following table aims to synthetically illustrate the results for the societal vulnerability analysis in PS4 – Mediterranean Spain.

PS4 RESVI Calculation – All Municipalities of the Province of Barcelona

RESVI Index – Municipalities of the Province of Barcelona

Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Abrera	0.39	0.58	0.57	0.61	0.27	0.73	0.65	0.57	0.61	0.27
Aguilar de Segarra	0.37	N/A	0.81	0.53	0.32	0.66	N/A	0.81	0.53	0.32
Aiguafreda	0.42	0.57	0.77	0.43	0.47	0.78	0.65	0.77	0.43	0.47
Alella	0.38	0.31	0.54	0.27	0.27	0.68	0.40	0.54	0.27	0.27
Alpens	0.38	N/A	0.83	0.27	0.49	0.70	N/A	0.83	0.27	0.49
Arenys de Mar	0.34	0.52	0.95	0.55	0.49	0.62	0.60	0.95	0.55	0.49
Arenys de Munt	0.40	0.58	0.74	0.56	0.45	0.74	0.66	0.74	0.56	0.45
Argençola	0.41	N/A	0.99	0.25	0.34	0.76	N/A	0.99	0.25	0.34
Argentona	0.40	0.56	0.34	0.47	0.48	0.74	0.65	0.34	0.47	0.48
Artés	0.41	0.62	0.97	0.66	0.28	0.76	0.70	0.97	0.66	0.28
Avià	0.41	0.58	1.00	0.58	0.27	0.75	0.67	1.00	0.58	0.27
Avinyó	0.42	0.59	0.71	0.69	0.39	0.77	0.68	0.71	0.69	0.39
Avinyonet del Penedès	0.39	0.64	0.86	0.61	0.15	0.72	0.73	0.86	0.61	0.15
Badalona	0.34	0.60	0.90	0.73	0.28	0.62	0.65	0.90	0.73	0.28
Badia del Vallès	0.31	0.69	N/A	0.86	0.51	0.56	0.73	N/A	0.86	0.51
Bagà	0.40	0.59	0.98	0.65	0.44	0.74	0.67	0.98	0.65	0.44
Balenyà	0.41	0.64	0.51	0.64	0.34	0.75	0.73	0.51	0.64	0.34
Balsareny	0.42	0.60	0.59	0.69	0.35	0.77	0.68	0.59	0.69	0.35
Barberà del Vallès	0.35	0.55	0.57	0.52	0.27	0.63	0.58	0.57	0.52	0.27
Barcelona	0.32	0.42	0.98	0.37	0.38	0.58	0.45	0.98	0.37	0.38

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Begues	0.42	0.45	0.98	0.23	0.34	0.77	0.54	0.98	0.23	0.34
Bellprat	0.35	N/A	0.79	0.78	0.33	0.63	N/A	0.79	0.78	0.33
Berga	0.39	0.62	0.60	0.60	0.40	0.71	0.70	0.60	0.60	0.40
Bigues i Riells del Fai	0.38	0.56	0.43	0.52	0.38	0.70	0.64	0.43	0.52	0.38
Borredà	0.36	N/A	0.84	0.70	0.51	0.68	N/A	0.84	0.70	0.51
Cabrera d'Anoia	0.39	0.68	0.35	0.55	0.42	0.72	0.76	0.35	0.55	0.42
Cabrera de Mar	0.38	0.35	0.75	0.22	0.43	0.69	0.43	0.75	0.22	0.43
Cabrils	0.39	0.31	0.95	0.18	0.33	0.73	0.39	0.95	0.18	0.33
Calaf	0.41	0.68	0.87	0.72	0.11	0.75	0.76	0.87	0.72	0.11
Calders	0.40	N/A	0.87	0.35	0.37	0.74	N/A	0.87	0.35	0.37
Caldes d'Estrac	0.34	0.54	N/A	0.37	0.26	0.62	0.61	N/A	0.37	0.26
Caldes de Montbui	0.39	0.57	0.56	0.50	0.42	0.72	0.66	0.56	0.50	0.42
Calella	0.39	0.67	0.88	0.65	0.43	0.71	0.74	0.88	0.65	0.43
Calldetenes	0.39	0.60	0.71	0.57	0.24	0.72	0.67	0.71	0.57	0.24
Callús	0.42	0.64	0.69	0.59	0.36	0.77	0.72	0.69	0.59	0.36
Calonge de Segarra	0.42	N/A	0.69	0.71	0.24	0.78	N/A	0.69	0.71	0.24
Campins	0.39	N/A	0.75	0.21	0.48	0.71	N/A	0.75	0.21	0.48
Canet de Mar	0.36	0.61	0.61	0.62	0.39	0.66	0.69	0.61	0.62	0.39
Canovelles	0.35	0.69	0.66	0.93	0.31	0.64	0.76	0.66	0.93	0.31
Cànoves i Samalús	0.39	0.58	0.67	0.51	0.44	0.72	0.67	0.67	0.51	0.44
Canyelles	0.40	0.57	0.70	0.50	0.29	0.74	0.65	0.70	0.50	0.29
Capellades	0.35	0.61	0.68	0.69	0.38	0.64	0.68	0.68	0.69	0.38
Capolat	0.44	N/A	0.68	0.15	0.47	0.82	N/A	0.68	0.15	0.47
Cardedeu	0.36	0.58	0.51	0.40	0.22	0.66	0.66	0.51	0.40	0.22
Cardona	0.42	0.60	0.48	0.91	0.32	0.77	0.69	0.48	0.91	0.32
Carme	0.42	N/A	0.81	0.54	0.33	0.77	N/A	0.81	0.54	0.33
Casserres	0.42	0.63	0.78	0.60	0.28	0.77	0.72	0.78	0.60	0.28
Castell de l'Areny	0.39	N/A	0.88	0.52	0.50	0.71	N/A	0.88	0.52	0.50
Castellar de n'Hug	0.37	N/A	0.82	0.62	0.47	0.70	N/A	0.82	0.62	0.47
Castellar del Riu	0.39	N/A	N/A	0.30	0.46	0.70	N/A	N/A	0.30	0.46
Castellar del Vallès	0.41	0.56	0.93	0.49	0.41	0.76	0.64	0.93	0.49	0.41
Castellbell i el Vilar	0.38	0.62	0.65	0.59	0.44	0.71	0.70	0.65	0.59	0.44
Castellbisbal	0.38	0.58	0.34	0.55	0.37	0.70	0.65	0.34	0.55	0.37
Castellcir	0.40	N/A	0.99	0.42	0.44	0.75	N/A	0.99	0.42	0.44
Castelldefels	0.35	0.46	0.89	0.35	0.29	0.64	0.52	0.89	0.35	0.29
Castellet i la Gornal	0.40	0.64	0.67	0.60	0.21	0.73	0.73	0.67	0.60	0.21
Castellfollit de Riubregós	0.40	N/A	0.98	0.32	0.20	0.73	N/A	0.98	0.32	0.20
Castellfollit del Boix	0.41	N/A	0.70	0.51	0.37	0.76	N/A	0.70	0.51	0.37
Castellgalí	0.41	0.62	0.99	0.60	0.40	0.75	0.71	0.99	0.60	0.40
Castellnou de Bages	0.41	0.59	0.94	0.46	0.39	0.75	0.67	0.94	0.46	0.39

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Castellolí	0.43	N/A	0.93	0.16	0.45	0.78	N/A	0.93	0.16	0.45
Castellterçol	0.38	0.62	0.89	0.59	0.45	0.71	0.70	0.89	0.59	0.45
Castellví de la Marca	0.40	0.64	0.95	0.68	0.16	0.75	0.74	0.95	0.68	0.16
Castellví de Rosanes	0.39	0.55	0.56	0.41	0.48	0.72	0.64	0.56	0.41	0.48
Centelles	0.40	0.59	0.94	0.59	0.37	0.74	0.67	0.94	0.59	0.37
Cercs	0.41	0.62	0.65	0.77	0.48	0.75	0.70	0.65	0.77	0.48
Cerdanyola del Vallès	0.37	0.54	0.86	0.45	0.47	0.67	0.62	0.86	0.45	0.47
Cervelló	0.40	0.52	0.55	0.42	0.46	0.74	0.60	0.55	0.42	0.46
Collbató	0.38	0.47	0.80	0.31	0.41	0.71	0.56	0.80	0.31	0.41
Collsuspina	0.44	N/A	0.98	0.49	0.42	0.80	N/A	0.98	0.49	0.42
Copons	0.45	N/A	0.99	0.33	0.32	0.81	N/A	0.99	0.33	0.32
Corbera de Llobregat	0.39	0.55	0.77	0.44	0.38	0.72	0.63	0.77	0.44	0.38
Cornellà de Llobregat	0.31	0.59	0.76	0.68	0.39	0.55	0.63	0.76	0.68	0.39
Cubelles	0.37	0.60	0.88	0.53	0.34	0.68	0.68	0.88	0.53	0.34
Dosrius	0.38	0.59	0.68	0.44	0.47	0.71	0.67	0.68	0.44	0.47
el Bruc	0.38	0.54	0.99	0.39	0.43	0.70	0.63	0.99	0.39	0.43
el Brull	0.38	N/A	0.85	0.18	0.44	0.70	N/A	0.85	0.18	0.44
el Masnou	0.32	0.50	0.61	0.32	0.30	0.57	0.58	0.61	0.32	0.30
el Papiol	0.39	0.57	0.68	0.45	0.51	0.71	0.65	0.68	0.45	0.51
el Pla del Penedès	0.41	0.65	0.68	0.58	0.08	0.75	0.74	0.68	0.58	0.08
el Pont de Vilomara i Rocafort	0.41	0.67	0.80	0.71	0.44	0.75	0.75	0.80	0.71	0.44
el Prat de Llobregat	0.38	0.59	0.72	0.67	0.29	0.69	0.65	0.72	0.67	0.29
els Hostalets de Pierola	0.41	0.63	0.75	0.59	0.38	0.76	0.72	0.75	0.59	0.38
els Prats de Rei	0.40	N/A	0.76	0.76	0.13	0.73	N/A	0.76	0.76	0.13
Esparreguera	0.40	0.60	0.99	0.62	0.41	0.73	0.67	0.99	0.62	0.41
Esplugues de Llobregat	0.34	0.42	0.62	0.57	0.44	0.60	0.46	0.62	0.57	0.44
Figaró-Montmany	0.40	0.67	N/A	0.52	0.50	0.74	0.75	N/A	0.52	0.50
Fígols	0.33	N/A	0.87	0.39	0.48	0.63	N/A	0.87	0.39	0.48
Fogars de la Selva	0.40	0.63	1.00	0.67	0.49	0.74	0.71	1.00	0.67	0.49
Fogars de Montclús	0.38	N/A	0.82	0.31	0.49	0.69	N/A	0.82	0.31	0.49
Folgueroles	0.40	0.55	1.00	0.37	0.22	0.75	0.64	1.00	0.37	0.22
Fonollosa	0.41	0.57	0.97	0.57	0.31	0.75	0.67	0.97	0.57	0.31
Font-rubí	0.40	0.65	1.00	0.52	0.15	0.73	0.74	1.00	0.52	0.15
Gaià	0.42	N/A	1.00	0.39	0.39	0.76	N/A	1.00	0.39	0.39
Gallifa	0.39	N/A	0.99	0.19	0.45	0.73	N/A	0.99	0.19	0.45

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Gavà	0.38	0.55	0.97	0.54	0.42	0.70	0.63	0.97	0.54	0.42
Gelida	0.40	0.63	1.00	0.49	0.35	0.74	0.71	1.00	0.49	0.35
Gironella	0.41	0.60	1.00	0.74	0.35	0.75	0.68	1.00	0.74	0.35
Gisclareny	0.34	N/A	1.00	0.02	0.41	0.58	N/A	1.00	0.02	0.41
Granera	0.32	N/A	1.00	0.29	0.38	0.59	N/A	1.00	0.29	0.38
Granollers	0.33	0.55	1.00	0.57	0.25	0.61	0.59	1.00	0.57	0.25
Gualba	0.41	0.61	1.00	0.33	0.49	0.74	0.69	1.00	0.33	0.49
Guardiola de Berguedà	0.39	N/A	0.99	0.69	0.48	0.72	N/A	0.99	0.69	0.48
Gurb	0.40	0.37	0.86	0.23	0.25	0.74	0.46	0.86	0.23	0.25
Igualada	0.34	0.59	0.95	0.57	0.13	0.62	0.64	0.95	0.57	0.13
Jorba	0.39	N/A	0.99	0.32	0.37	0.73	N/A	0.99	0.32	0.37
l'Ametlla del Vallès	0.37	0.37	0.66	0.25	0.31	0.68	0.45	0.66	0.25	0.31
l'Espunyola	0.41	N/A	1.00	0.66	0.36	0.75	N/A	1.00	0.66	0.36
l'Esquirol	0.41	0.58	0.98	0.50	0.39	0.75	0.67	0.98	0.50	0.39
l'Estany	0.41	N/A	1.00	0.56	0.48	0.75	N/A	1.00	0.56	0.48
l'Hospitalet de Llobregat	0.30	0.59	0.67	0.77	0.31	0.55	0.60	0.67	0.77	0.31
la Garriga	0.39	0.56	0.66	0.42	0.43	0.73	0.64	0.66	0.42	0.43
la Granada	0.37	0.62	0.98	0.47	0.13	0.68	0.70	0.98	0.47	0.13
la Llacuna	0.41	N/A	0.99	0.51	0.37	0.74	N/A	0.99	0.51	0.37
la Llagosta	0.33	0.62	0.66	0.85	0.59	0.60	0.66	0.66	0.85	0.59
la Nou de Berguedà	0.38	N/A	1.00	N/A	0.51	0.70	N/A	1.00	N/A	0.51
la Palma de Cervelló	0.39	0.52	1.00	N/A	0.48	0.71	0.60	1.00	N/A	0.48
la Pobla de Claramunt	0.41	0.64	1.00	0.59	0.40	0.76	0.73	1.00	0.59	0.40
la Pobla de Lillet	0.43	0.59	0.98	0.90	0.50	0.78	0.68	0.98	0.90	0.50
la Quar	0.41	N/A	1.00	0.83	0.45	0.75	N/A	1.00	0.83	0.45
la Roca del Vallès	0.39	0.54	0.98	0.46	0.42	0.71	0.62	0.98	0.46	0.42
la Torre de Claramunt	0.37	0.63	1.00	0.61	0.31	0.69	0.72	1.00	0.61	0.31
les Cabanyes	0.39	N/A	1.00	0.44	0.02	0.71	N/A	1.00	0.44	0.02
les Franqueses del Vallès	0.37	0.64	0.97	0.63	0.24	0.69	0.72	0.97	0.63	0.24
les Masies de Roda	0.40	N/A	0.99	0.51	0.28	0.74	N/A	0.99	0.51	0.28
les Masies de Voltregà	0.40	0.58	0.97	N/A	0.32	0.74	0.67	0.97	N/A	0.32
Lliçà d'Amunt	0.36	0.56	0.66	0.57	0.28	0.65	0.63	0.66	0.57	0.28
Lliçà de Vall	0.38	0.51	0.99	0.58	0.27	0.69	0.56	0.99	0.58	0.27
Llinars del Vallès	0.37	0.59	0.99	0.54	0.42	0.68	0.67	0.99	0.54	0.42
Lluçà	0.43	N/A	0.98	0.32	0.44	0.80	N/A	0.98	0.32	0.44
Malgrat de Mar	0.37	0.66	0.99	0.69	0.19	0.68	0.73	0.99	0.69	0.19

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Malla	0.40	N/A	0.98	0.17	0.20	0.73	N/A	0.98	0.17	0.20
Manlleu	0.39	0.65	0.93	0.89	0.16	0.71	0.72	0.93	0.89	0.16
Manresa	0.37	0.62	0.97	0.62	0.36	0.67	0.69	0.97	0.62	0.36
Marganell	0.38	N/A	1.00	0.40	0.45	0.71	N/A	1.00	0.40	0.45
Martorell	0.35	0.64	0.67	0.81	0.43	0.64	0.70	0.67	0.81	0.43
Martorelles	0.38	0.53	1.00	0.64	0.23	0.70	0.57	1.00	0.64	0.23
Masquefa	0.39	0.64	0.67	0.60	0.23	0.71	0.72	0.67	0.60	0.23
Matadepera	0.40	0.30	1.00	0.08	0.41	0.73	0.38	1.00	0.08	0.41
Mataró	0.35	0.64	1.00	0.71	0.33	0.64	0.71	1.00	0.71	0.33
Mediona	0.41	0.68	0.99	0.68	0.33	0.76	0.77	0.99	0.68	0.33
Moià	0.40	0.66	0.95	0.59	0.41	0.74	0.74	0.95	0.59	0.41
Molins de Rei	0.38	0.51	0.67	0.38	0.48	0.71	0.57	0.67	0.38	0.48
Mollet del Vallès	0.34	0.58	0.65	0.71	0.33	0.63	0.62	0.65	0.71	0.33
Monistrol de Calders	0.40	N/A	1.00	0.68	0.39	0.73	N/A	1.00	0.68	0.39
Monistrol de Montserrat	0.38	0.63	N/A	0.58	0.42	0.69	0.72	N/A	0.58	0.42
Montcada i Reixac	0.37	0.62	0.64	0.67	0.45	0.67	0.69	0.64	0.67	0.45
Montclar	0.41	N/A	1.00	0.52	0.27	0.76	N/A	1.00	0.52	0.27
Montesquiu	0.39	0.64	1.00	0.53	0.51	0.71	0.73	1.00	0.53	0.51
Montgat	0.32	0.53	N/A	0.38	0.68	0.57	0.59	N/A	0.38	0.68
Montmajor	0.45	N/A	0.91	0.52	0.30	0.80	N/A	0.91	0.52	0.30
Montmaneu	0.38	N/A	0.88	0.64	0.21	0.69	N/A	0.88	0.64	0.21
Montmeló	0.35	0.58	0.40	0.73	0.18	0.65	0.62	0.40	0.73	0.18
Montornès del Vallès	0.39	0.60	0.50	0.74	0.31	0.71	0.65	0.50	0.74	0.31
Montseny	0.38	N/A	0.82	0.56	0.49	0.70	N/A	0.82	0.56	0.49
Muntanyola	0.39	N/A	0.66	0.33	0.47	0.72	N/A	0.66	0.33	0.47
Mura	0.40	N/A	0.99	0.30	0.45	0.73	N/A	0.99	0.30	0.45
Navarcles	0.40	0.59	0.59	0.66	0.28	0.74	0.67	0.59	0.66	0.28
Navàs	0.42	0.61	0.45	0.67	0.36	0.78	0.70	0.45	0.67	0.36
Òdena	0.40	0.66	0.38	0.63	0.29	0.74	0.74	0.38	0.63	0.29
Olèrdola	0.40	0.61	0.80	0.54	0.19	0.73	0.69	0.80	0.54	0.19
Olesa de Bonesvalls	0.40	0.59	0.71	0.58	0.37	0.74	0.67	0.71	0.58	0.37
Olesa de Montserrat	0.40	0.62	0.36	0.62	0.39	0.74	0.69	0.36	0.62	0.39
Olivella	0.41	0.57	0.87	0.34	0.27	0.75	0.65	0.87	0.34	0.27
Olost	0.42	0.60	0.97	0.63	0.31	0.78	0.69	0.97	0.63	0.31
Olvan	0.42	N/A	0.81	0.60	0.34	0.77	N/A	0.81	0.60	0.34
Orís	0.40	N/A	0.98	0.32	0.41	0.74	N/A	0.98	0.32	0.41
Oristà	0.42	N/A	0.97	0.60	0.33	0.77	N/A	0.97	0.60	0.33
Orpí	0.46	N/A	0.86	0.46	0.35	0.82	N/A	0.86	0.46	0.35

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Òrrius	0.42	N/A	0.99	0.22	0.48	0.78	N/A	0.99	0.22	0.48
Pacs del Penedès	0.37	N/A	0.95	0.40	0.10	0.67	N/A	0.95	0.40	0.10
Palafolls	0.39	0.65	0.43	0.59	0.39	0.73	0.73	0.43	0.59	0.39
Palau-solità i Plegamans	0.39	0.56	0.32	0.49	0.23	0.71	0.62	0.32	0.49	0.23
Pallejà	0.38	0.52	0.62	0.45	0.51	0.70	0.60	0.62	0.45	0.51
Parets del Vallès	0.34	0.55	0.65	0.56	0.32	0.63	0.59	0.65	0.56	0.32
Perafita	0.42	N/A	0.86	0.53	0.40	0.76	N/A	0.86	0.53	0.40
Piera	0.41	0.66	0.78	0.70	0.28	0.76	0.74	0.78	0.70	0.28
Pineda de Mar	0.37	0.68	0.59	0.80	0.31	0.67	0.75	0.59	0.80	0.31
Polinyà	0.39	0.60	0.77	0.58	0.21	0.71	0.67	0.77	0.58	0.21
Pontons	0.39	N/A	0.95	0.65	0.38	0.71	N/A	0.95	0.65	0.38
Prats de Lluçanès	0.42	0.59	0.95	0.74	0.29	0.77	0.68	0.95	0.74	0.29
Premià de Dalt	0.36	0.47	1.00	0.39	0.35	0.65	0.55	1.00	0.39	0.35
Premià de Mar	0.32	0.52	0.63	0.53	0.23	0.58	0.55	0.63	0.53	0.23
Puig-reig	0.41	0.62	0.38	0.75	0.36	0.76	0.71	0.38	0.75	0.36
Puigdàlber	0.38	N/A	0.70	0.53	0.00	0.68	N/A	0.70	0.53	0.00
Pujalt	0.42	N/A	0.67	0.32	0.13	0.75	N/A	0.67	0.32	0.13
Rajadell	0.28	N/A	0.98	0.44	0.41	0.50	N/A	0.98	0.44	0.41
Rellinars	0.40	N/A	N/A	0.42	0.45	0.75	N/A	N/A	0.42	0.45
Ripollet	0.33	0.60	0.45	0.66	0.43	0.60	0.64	0.45	0.66	0.43
Roda de Ter	0.35	0.59	0.93	0.72	0.12	0.64	0.64	0.93	0.72	0.12
Rubí	0.39	0.62	0.33	0.58	0.31	0.71	0.69	0.33	0.58	0.31
Rubió	0.38	N/A	0.83	0.52	0.33	0.68	N/A	0.83	0.52	0.33
Rupit i Pruit	0.43	N/A	0.75	0.59	0.49	0.78	N/A	0.75	0.59	0.49
Sabadell	0.36	0.58	0.58	0.64	0.29	0.66	0.63	0.58	0.64	0.29
Sagàs	0.40	N/A	0.83	0.12	0.28	0.74	N/A	0.83	0.12	0.28
Saldes	0.37	N/A	0.90	0.64	0.45	0.67	N/A	0.90	0.64	0.45
Sallent	0.42	0.60	0.32	0.65	0.35	0.78	0.68	0.32	0.65	0.35
Sant Adrià de Besòs	0.31	0.62	0.61	0.76	0.50	0.57	0.65	0.61	0.76	0.50
Sant Agustí de Lluçanès	0.40	N/A	0.68	0.41	0.42	0.73	N/A	0.68	0.41	0.42
Sant Andreu de la Barca	0.36	0.60	0.65	0.68	0.32	0.66	0.64	0.65	0.68	0.32
Sant Andreu de Llavaneres	0.37	0.48	0.70	0.31	0.42	0.68	0.57	0.70	0.31	0.42
Sant Antoni de Vilamajor	0.38	0.54	0.64	0.44	0.24	0.69	0.62	0.64	0.44	0.24
Sant Bartomeu del Grau	0.41	N/A	0.87	0.57	0.39	0.74	N/A	0.87	0.57	0.39
Sant Boi de Llobregat	0.37	0.59	0.65	0.68	0.31	0.68	0.64	0.65	0.68	0.31

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Sant Boi de Lluçanès	0.42	N/A	0.73	0.73	0.39	0.76	N/A	0.73	0.73	0.39
Sant Cebrià de Vallalta	0.40	0.60	0.59	0.44	0.44	0.74	0.69	0.59	0.44	0.44
Sant Celoni	0.40	0.64	0.98	0.63	0.51	0.75	0.72	0.98	0.63	0.51
Sant Climent de Llobregat	0.39	0.58	0.67	0.43	0.44	0.72	0.66	0.67	0.43	0.44
Sant Cugat del Vallès	0.36	0.36	0.45	0.06	0.48	0.66	0.44	0.45	0.06	0.48
Sant Cugat Sesgarrigues	0.40	0.62	0.88	0.56	0.05	0.74	0.70	0.88	0.56	0.05
Sant Esteve de Palautordera	0.41	0.53	1.00	0.27	0.40	0.77	0.61	1.00	0.27	0.40
Sant Esteve Sesrovires	0.40	0.55	0.42	0.48	0.28	0.74	0.63	0.42	0.48	0.28
Sant Feliu de Codines	0.38	0.63	0.92	0.52	0.45	0.70	0.71	0.92	0.52	0.45
Sant Feliu de Llobregat	0.38	0.52	0.92	0.54	0.41	0.70	0.58	0.92	0.54	0.41
Sant Feliu Sasserra	0.43	N/A	0.95	0.67	0.33	0.77	N/A	0.95	0.67	0.33
Sant Fost de Campsentelles	0.40	0.53	0.34	0.60	0.36	0.73	0.61	0.34	0.60	0.36
Sant Fruitós de Bages	0.38	0.51	0.60	0.53	0.31	0.70	0.59	0.60	0.53	0.31
Sant Hipòlit de Voltregà	0.32	0.55	0.88	0.70	0.15	0.58	0.62	0.88	0.70	0.15
Sant Iscle de Vallalta	0.40	0.60	N/A	0.47	0.49	0.75	0.69	N/A	0.47	0.49
Sant Jaume de Frontanyà	0.40	N/A	0.91	0.41	0.48	0.68	N/A	0.91	0.41	0.48
Sant Joan de Vilatorrada	0.39	0.63	0.30	0.75	0.25	0.72	0.70	0.30	0.75	0.25
Sant Joan Despí	0.33	0.51	0.94	0.49	0.41	0.61	0.57	0.94	0.49	0.41
Sant Julià de Cerdanyola	0.36	N/A	0.71	0.38	0.48	0.67	N/A	0.71	0.38	0.48
Sant Julià de Vilatorta	0.40	0.49	0.99	0.37	0.41	0.74	0.57	0.99	0.37	0.41
Sant Just Desvern	0.41	0.23	0.40	0.18	0.36	0.74	0.30	0.40	0.18	0.36
Sant Llorenç d'Hortons	0.41	0.59	0.97	0.46	0.18	0.77	0.68	0.97	0.46	0.18
Sant Llorenç Savall	0.41	0.61	0.67	0.65	0.35	0.76	0.69	0.67	0.65	0.35
Sant Martí d'Albars	0.43	N/A	0.68	0.33	0.31	0.79	N/A	0.68	0.33	0.31
Sant Martí de Centelles	0.40	0.64	0.84	0.46	0.43	0.74	0.73	0.84	0.46	0.43
Sant Martí de Tous	0.42	0.60	0.65	0.35	0.34	0.78	0.69	0.65	0.35	0.34

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Sant Martí Sarroca	0.41	0.68	0.28	0.62	0.14	0.76	0.77	0.28	0.62	0.14
Sant Martí Sesgueioles	0.39	N/A	0.99	0.54	0.07	0.74	N/A	0.99	0.54	0.07
Sant Mateu de Bages	0.42	N/A	0.67	0.46	0.38	0.77	N/A	0.67	0.46	0.38
Sant Pere de Ribes	0.40	0.61	0.65	0.56	0.29	0.73	0.69	0.65	0.56	0.29
Sant Pere de Riudebitlles	0.39	0.62	1.00	0.74	0.36	0.71	0.69	1.00	0.74	0.36
Sant Pere de Torelló	0.40	0.60	0.98	0.63	0.46	0.73	0.69	0.98	0.63	0.46
Sant Pere de Vilamajor	0.40	0.56	0.98	0.40	0.43	0.73	0.64	0.98	0.40	0.43
Sant Pere Sallavinera	0.42	N/A	0.99	0.33	0.29	0.75	N/A	0.99	0.33	0.29
Sant Pol de Mar	0.37	0.55	0.67	0.33	0.49	0.68	0.63	0.67	0.33	0.49
Sant Quintí de Mediona	0.41	0.71	1.00	0.81	0.28	0.75	0.79	1.00	0.81	0.28
Sant Quirze de Besora	0.41	0.61	0.99	0.79	0.45	0.75	0.69	0.99	0.79	0.45
Sant Quirze del Vallès	0.37	0.42	0.65	0.23	0.44	0.67	0.48	0.65	0.23	0.44
Sant Quirze Safaja	0.37	N/A	1.00	0.26	0.42	0.68	N/A	1.00	0.26	0.42
Sant Sadurní d'Anoia	0.40	0.59	0.67	0.61	0.22	0.74	0.67	0.67	0.61	0.22
Sant Sadurní d'Osormort	0.32	N/A	1.00	0.38	0.52	0.59	N/A	1.00	0.38	0.52
Sant Salvador de Guardiola	0.40	0.61	0.99	0.58	0.42	0.73	0.70	0.99	0.58	0.42
Sant Vicenç de Castellet	0.40	0.67	0.66	0.77	0.41	0.74	0.75	0.66	0.77	0.41
Sant Vicenç de Montalt	0.37	0.38	1.00	0.24	0.43	0.69	0.46	1.00	0.24	0.43
Sant Vicenç de Torelló	0.39	0.54	1.00	0.55	0.27	0.72	0.62	1.00	0.55	0.27
Sant Vicenç dels Horts	0.35	0.60	0.66	0.69	0.40	0.63	0.66	0.66	0.69	0.40
Santa Cecília de Voltregà	0.39	N/A	1.00	0.41	0.26	0.71	N/A	1.00	0.41	0.26
Santa Coloma de Cervelló	0.36	0.54	0.66	0.39	0.37	0.66	0.62	0.66	0.39	0.37
Santa Coloma de Gramenet	0.34	0.64	0.67	0.92	0.24	0.61	0.68	0.67	0.92	0.24
Santa Eugènia de Berga	0.41	0.60	0.99	0.74	0.10	0.75	0.68	0.99	0.74	0.10

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Santa Eulàlia de Riuprimer	0.43	0.55	0.99	0.51	N/A	0.80	0.63	0.99	0.51	N/A
Santa Eulàlia de Ronçana	0.35	0.55	0.65	0.53	0.30	0.65	0.63	0.65	0.53	0.30
Santa Fe del Penedès	0.41	N/A	1.00	0.50	0.06	0.76	N/A	1.00	0.50	0.06
Santa Margarida de Montbui	0.43	0.75	0.99	0.86	0.30	0.79	0.83	0.99	0.86	0.30
Santa Margarida i els Monjos	0.40	0.64	0.65	0.70	0.18	0.74	0.71	0.65	0.70	0.18
Santa Maria d'Oló	0.43	0.60	0.99	0.63	0.47	0.78	0.69	0.99	0.63	0.47
Santa Maria de Besora	0.40	N/A	1.00	0.35	0.48	0.73	N/A	1.00	0.35	0.48
Santa Maria de Martorelles	0.40	N/A	N/A	0.39	0.47	0.74	N/A	N/A	0.39	0.47
Santa Maria de Merlès	0.43	N/A	1.00	0.44	0.38	0.79	N/A	1.00	0.44	0.38
Santa Maria de Miralles	0.41	N/A	1.00	0.55	0.35	0.75	N/A	1.00	0.55	0.35
Santa Maria de Palautordera	0.39	0.61	0.65	0.54	0.36	0.72	0.69	0.65	0.54	0.36
Santa Perpètua de Mogoda	0.35	0.60	0.67	0.64	0.31	0.63	0.66	0.67	0.64	0.31
Santa Susanna	0.39	0.65	1.00	0.46	0.42	0.72	0.73	1.00	0.46	0.42
Santpedor	0.40	0.58	0.96	0.49	0.15	0.73	0.66	0.96	0.49	0.15
Sentmenat	0.40	0.60	0.67	0.52	0.38	0.74	0.68	0.67	0.52	0.38
Seva	0.39	0.54	0.98	0.42	0.40	0.72	0.63	0.98	0.42	0.40
Sitges	0.38	0.46	1.00	0.27	0.33	0.70	0.54	1.00	0.27	0.33
Sobremunt	0.44	N/A	1.00	0.78	0.47	0.84	N/A	1.00	0.78	0.47
Sora	0.41	N/A	0.99	0.43	0.47	0.74	N/A	0.99	0.43	0.47
Subirats	0.40	0.62	0.64	0.55	0.26	0.73	0.71	0.64	0.55	0.26
Súria	0.40	0.60	0.98	0.69	0.39	0.75	0.68	0.98	0.69	0.39
Tagamanent	0.39	N/A	1.00	0.29	0.51	0.73	N/A	1.00	0.29	0.51
Talamanca	0.41	N/A	1.00	0.22	0.35	0.73	N/A	1.00	0.22	0.35
Taradell	0.41	0.56	0.64	0.53	0.30	0.75	0.64	0.64	0.53	0.30
Tavèrnoles	0.42	N/A	0.99	0.21	0.41	0.77	N/A	0.99	0.21	0.41
Tavertet	0.42	N/A	0.99	0.38	0.48	0.77	N/A	0.99	0.38	0.48
Teià	0.35	0.37	1.00	0.33	0.30	0.63	0.45	1.00	0.33	0.30
Terrassa	0.37	0.60	0.99	0.60	0.43	0.68	0.67	0.99	0.60	0.43
Tiana	0.40	0.41	0.99	0.17	0.30	0.74	0.49	0.99	0.17	0.30
Tona	0.40	0.60	0.59	0.61	0.31	0.74	0.68	0.59	0.61	0.31
Tordera	0.41	0.69	0.66	0.71	0.42	0.75	0.78	0.66	0.71	0.42
Torelló	0.39	0.59	0.65	0.68	0.22	0.71	0.67	0.65	0.68	0.22

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Municipality	Weighted values					Non-weighted values				
	Soc	Eco	Ist	H Cap	Env	Soc	Eco	Ist	H Cap	Env
Torrelavit	0.40	0.61	0.95	0.53	0.19	0.73	0.70	0.95	0.53	0.19
Torrelles de Foix	0.40	0.73	1.00	0.79	0.28	0.73	0.82	1.00	0.79	0.28
Torrelles de Llobregat	0.42	0.54	0.67	0.31	0.44	0.78	0.62	0.67	0.31	0.44
Ullastrell	0.41	0.53	1.00	0.33	0.41	0.75	0.62	1.00	0.33	0.41
Vacarisses	0.39	0.59	0.67	0.43	0.46	0.73	0.67	0.67	0.43	0.46
Vallbona d'Anoia	0.41	0.60	1.00	0.64	0.47	0.75	0.68	1.00	0.64	0.47
Vallcebre	0.38	N/A	1.00	0.70	0.46	0.70	N/A	1.00	0.70	0.46
Vallgorguina	0.40	0.58	1.00	0.29	0.51	0.74	0.66	1.00	0.29	0.51
Vallirana	0.40	0.57	0.67	0.55	0.36	0.73	0.64	0.67	0.55	0.36
Vallromanes	0.36	0.38	1.00	0.18	0.49	0.67	0.46	1.00	0.18	0.49
Veciana	0.42	N/A	1.00	0.58	0.24	0.75	N/A	1.00	0.58	0.24
Vic	0.37	0.60	0.45	0.64	0.19	0.69	0.67	0.45	0.64	0.19
Vilada	0.40	N/A	1.00	0.54	0.51	0.72	N/A	1.00	0.54	0.51
Viladecans	0.37	0.58	0.67	0.62	0.35	0.67	0.64	0.67	0.62	0.35
Viladecavalls	0.40	0.54	0.67	0.43	0.53	0.74	0.62	0.67	0.43	0.53
Vilafranca del Penedès	0.36	0.61	0.52	0.66	0.18	0.65	0.68	0.52	0.66	0.18
Vilalba Sasserra	0.40	N/A	0.69	0.52	0.50	0.75	N/A	0.69	0.52	0.50
Vilanova de Sau	0.44	N/A	0.82	0.27	0.48	0.80	N/A	0.82	0.27	0.48
Vilanova del Camí	0.41	0.69	0.43	0.83	0.34	0.75	0.76	0.43	0.83	0.34
Vilanova del Vallès	0.40	0.45	0.36	0.39	0.36	0.74	0.53	0.36	0.39	0.36
Vilanova i la Geltrú	0.38	0.60	0.96	0.56	0.26	0.70	0.67	0.96	0.56	0.26
Vilassar de Dalt	0.39	0.49	1.00	0.42	0.42	0.71	0.57	1.00	0.42	0.42
Vilassar de Mar	0.35	0.48	1.00	0.31	0.15	0.63	0.54	1.00	0.31	0.15
Vilobí del Penedès	0.41	0.62	1.00	0.63	0.01	0.75	0.71	1.00	0.63	0.01
Viver i Serrateix	0.43	N/A	0.99	0.56	0.35	0.79	N/A	0.99	0.56	0.35

Implementation of the Societal Vulnerability Index in PS5 – Mediterranean Greece

The following table aims to illustrate the results for the societal vulnerability analysis in PS5 – Mediterranean Greece.

PS5 RESVI Calculation – NUTS-2 Eastern Attica Region

RESVI Index – NUTS-2 Eastern Attica Region

Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
Social	Family structure	N/A	0.37	Percentage of people married	N/A	0.41
				Percentage of single parent families	N/A	0.34

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Dimension	Indicator	Weighted	Non-weighted	Proxy	Weighted	Non-weighted
	Gender	N/A	0.44	Percentage of women	N/A	0.44
Total Social					**N/A**	**0.41**
Economic	Wealth and Socio-economic status	N/A	0.44	Percentage of home ownership	N/A	0.44
	Primary sector	N/A	0.52	Livestock density	N/A	0.52
Total Economic					**N/A**	**0.48**
Human Capital	Educational level	N/A	0.53	Percentage population with elementary school level	N/A	0.50
				Percentage population with secondary school level	N/A	0.49
				Percentage population with higher educational level	N/A	0.61
	Health Services	N/A	0.44	Population with access to sanitation (%)	N/A	0.44
Total Human Capital					**N/A**	**0.49**
Environmental	Infrastructure	N/A	0.52	Hotels and motels per square kilometre	N/A	0.52
	Land Use and Land Coverage	N/A	0.43	Percentage of land under agriculture including plantation / forestry	N/A	0.38
				No. of agriculture farms / 10,000 sq. km	N/A	0.47
	Residential property	N/A	0.62	Percentage of vacant housing	N/A	0.62
Total Environmental					**N/A**	**0.52**

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Annex A2: A122 – Damage functions review

Introduction

The definition of "damage" refers to the material losses consequent on hazardous events (Vanneuville et al. (2005). In general, damage functions increase with the magnitude of the extreme event such as a flood or a fire, and eventually exhibit saturation (Steinhäuser et al 2015). For the estimation of structural damages from natural disasters, the most popular and internationally accepted approach is the application of damage functions. In general, damage functions characterise the mathematical connection between hazard magnitude and damage and thereby make up an essential part of the modelling. Damage functions in the literature are either described as mathematical expressions or illustrated as graphs. In graphs, the x-axis describes the hazard severity. The y-axis represents the estimated damages. They can either be calculated in relative or absolute figures. Absolute damage functions allocate monetary losses to hazard severity. In contrast, relative damage functions (consensual recommendation) show damages as proportion of the maximum possible damage. (EU-CIRCLE project report, 2018).

Although recent research confirms the multiplicity of influencing variables, there is often no comprehensive approach for including all factors in the modelling. Based on the input data at disposal for the modelling, a description of the hazard severity needs to be formulated.

Therefore, the following three phases of assessment are determined as the hazard, the damage and impact assessments:

1. **Hazard assessment**: in the beginning, during the fire risk assessment, the historical frequency of occurrence of the hazard (forest fires in this case) is measured along with its various degrees of intensity and severity for the specific area of interest These parameters can be provided through climate historical data, fire spread and smoke dispersion models. After the determination of the hazard assessment, the damage assessment is following based on a scenario approach.
2. **Damage assessment:** evaluates the direct consequences caused by the fire event on the CI network operation that is exposed to wildfires or smoke. Direct consequences are usually caused by physical and operational damage, the corresponding business interruption, and the management to handling the fire. These damages should be estimated for different types of assets or network of the examined infrastructure under different time steps and different types and intensities of hazard, that should be defined for the assessment. The results of the damage assessment employ as a guide to the evaluation of the critical service mitigation that affects the performance of the entire set of the interconnected elements modelled as networks.
3. **Impact assessment**: The first impact is initially occurred on an asset level and typically describes physical damages. Functional damages are consequences of structural asset damage. After the completion of the estimation of all types of damages in the entire system, impacts are then propagated to the users of the system (impact assessment), which is the final phase.

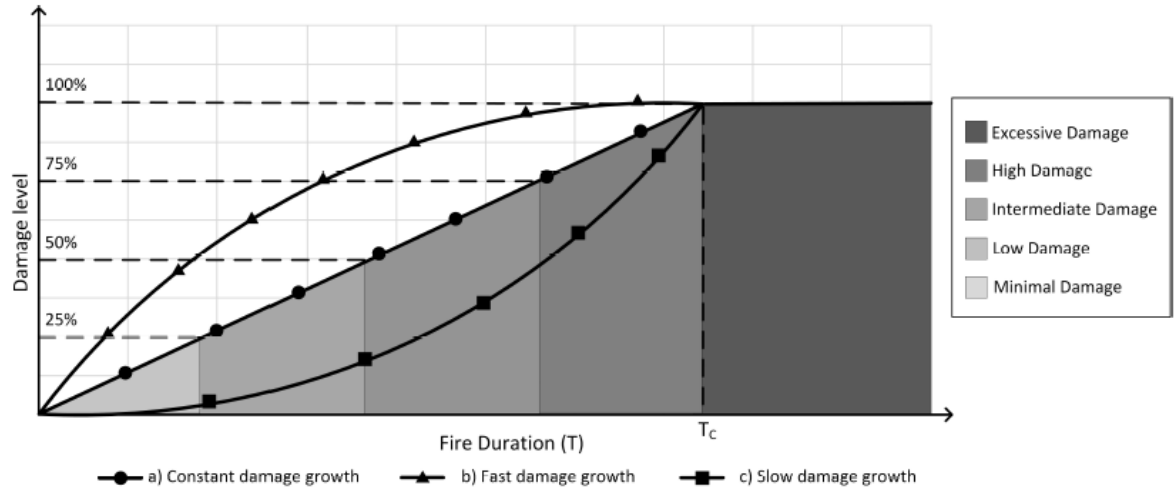
In addition, damages are distinguished in two types as: **direct** damages that concern the losses resulting from direct contact with the forest fire (e.g., burnt electricity transmission lines) and **indirect** damages that include

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losses resulting from the event but not from direct impact, e.g., limited visibility of transportation system due to smoke.

Damage Functions for the assessment of Wildfires damages

Alutaibi (2017) provides general equations for the assessment of wildfire damages. The author distinguishes two types of functions: the linear and the non-linear damage function which evaluate fast and slow damage growth processes. The author also highlights that the fire duration is associated to a particular level of damage. In addition, the level of damage is influenced by several parameters (e.g., fuel type, wind speed and direction).



Differences between damage functions showing the levels of damage as a function of the fire duration (Alutaibi, 2017, Illustration of the damage function)

Thus, Alutaibi (2017) suggests idealised courses of damage functions distinguished by linear, slow and fast damage growth, depending on the slope of the damage function, as illustrated in Figure 28.

So, in this section, for the assessment of wildfires damages, damage functions will be presented per infrastructure.

Electricity (Energy sector):

In the case of Electricity Infrastructure, the damages are distinguished according to their influence on the asset. During high exposure the transmission tower is directly affected by the flames. A medium exposure occurs when the height of the vegetation in close vicinity of the tower is low and big trees are located at some distance. The maximum damage is reached after a fire duration of 70 minutes. Damages to the galvanising is expected to occur after 40 minutes. Basically, the function is the shifted damage function for high exposure. According to this simple procedure different damage function can be estimated for different exposures.

Table 15 provides a summary of the main impacts on the electricity and road networks alongside some design thresholds.

Forest fires impact on electricity infrastructures and associated threshold by Sfetsos et al 2021

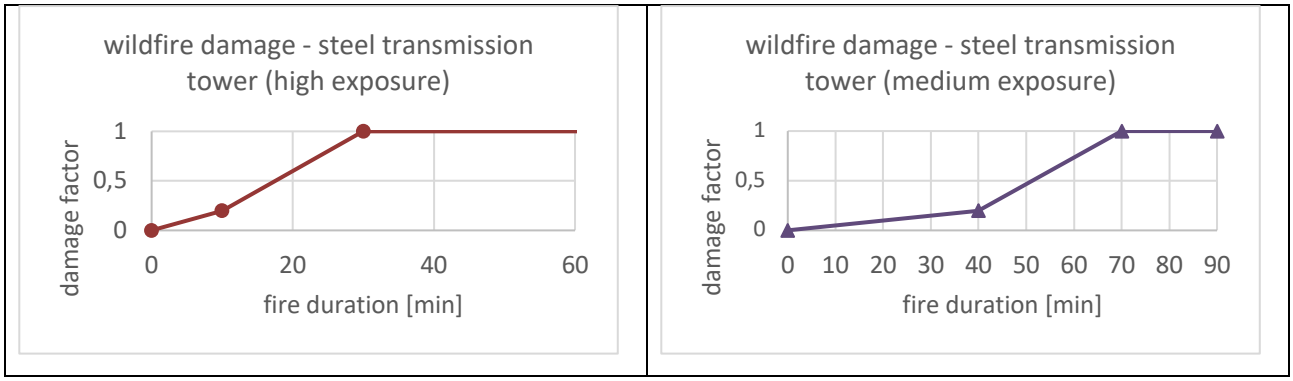
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	Asset	Impact Threshold
Electricity	Distribution lines Extra-High Voltage (EHV) transmission lines	Structural threshold: Temperature = 500–600 °C
	Distribution substations Transformer Electrical grid operation	Functional threshold: Temperature = 420 °C (melting point of zinc)
	Functional threshold: PM2.5 concentration is > 350 µg/m3	Functional threshold: PM2.5 concentration is > 350 µg/m3
	Step up_down substations	Same threshold values as described in EHV transmission lines.
	Wooden pylon	Flame temperature (>650 °C)

Calculation of wildfire damage to steel transmission towers

Transmission towers can be designed using different materials. Here the focus is set on steel transmission towers. An example for the calculation of fire damage to steel transmission towers is presented is the following lines and figures:

Errore. L'origine riferimento non è stata trovata. on the left depicts the attempt for the estimation of a damage function for a steel transmission tower that is directly affected by wildfire while on the right, steel transmission towers exposed to medium wildfire impacts. Basically, the function is the shifted damage function for high exposure.



Wildfire damage function for steel transmission towers directly affected by wildfire (left), wildfire damage function for steel transmission towers affected by wildfire of medium exposure (right)

Required Inputs:

i. Fireline intensity I (kW/m)

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ii. Rate of Spread (m/min)

iii. Ambient temperature Ta(C)

iv. h = height above ground;

v. Output:

vi. Structural damage (%)

Steps:

1. Fireline intensity per computational cell (I)
2. Estimate temperature eq[5] of Alexander

   ΔT (C) = 3.9 * $I^{2/3}$ /h -> temperature at height h above ambient temperature

   T (h) = Ta(h) + ΔT (h) -> temperature at a computational cell
3. Find strength of structure

   Use Figure 1, selecting appropriate plot – depending on material.
4. Determine HIGH or MEDIUM exposure (our proposal)

   If strength factor (y-axis of Fig 1) < 0.6 , THEN HIGH EXPOSURE (use Fig 2)

   If strength factor (y-axis of Fig 1) > 0.6 , THEN MED EXPOSURE (use Fig 3)
5. Determine fire duration

   Time is approximated as Computational Cell length (m) / Rate of Spread (m/min)

   Suggested value for computational cell = 50 m
6. Find damage

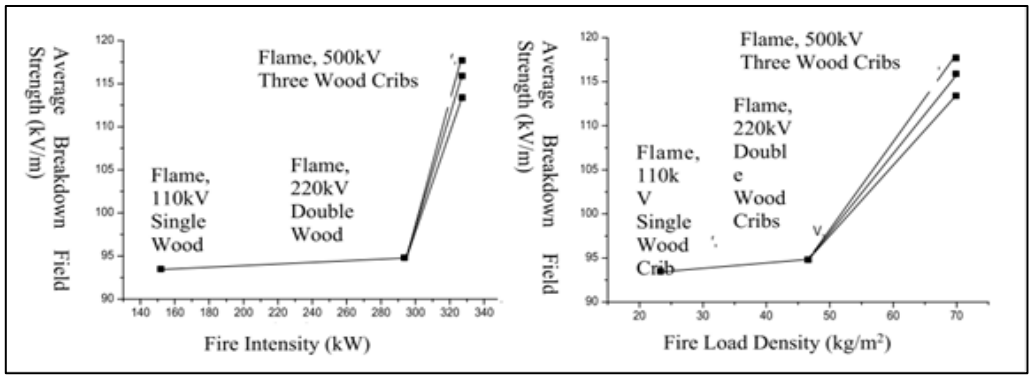
   Use Figure 29 (left or right) (based on step 4)

   Fire duration from step 5.

   Damage is (in our opinion) is structural damage leading to replacement / maintenance costs.

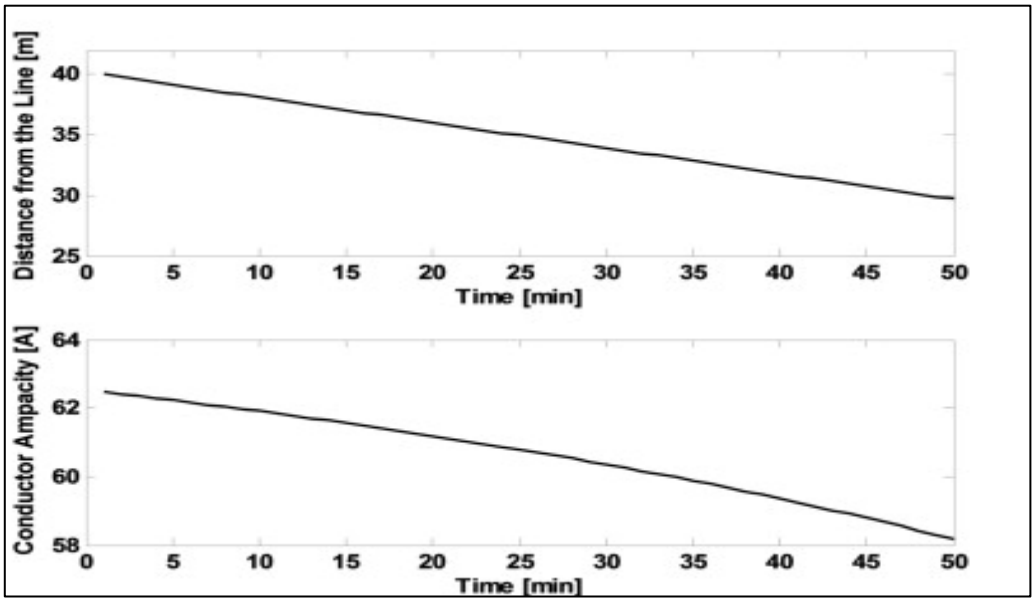
   Operational damage TBD

Damage functions for operational damage to electricity assets



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The effect of fire intensity and fire load density on breakdown voltage and distance in fire (You et al., 2013)



Variations in the conductor's ampacity as fire approaches the line (Choobineh et al., 2015)

Transportation

Mostafaei *et al.* (2014) analysed damage to bridges based on two cases. The authors conclude that a collapse, which is tantamount to total damage, occurs in short time of fire duration when a reinforced concrete bridge is directly affected by the fire.

In this paragraph we present the limit of such materials with respect to high temperatures as a result of a wildfire or forest fires. The impact on the ICT sector is the potential loss of lines or towers after the exposure in fire resulting to an outage of services. For example, wood poles ignite but don't mechanically fail until a substantial portion of the diameter has been burned (Smith, 2014). Galvanized steel poles can fail catastrophically at temperatures above 515 °C; however, fire resistant steel alloys and temperature resistant coatings can be used to extend time to failure. Table 16 presents the temperature limit for different materials that are used for the construction of towers and lines (Butler et al. 2015).

Temperature limit of materials (towers, masts and lines)

Material	Temperature	Reaction
Wood	300 °C	Wood chars indefinitely
Steel	538 °C	Steel softens and breaks
Aluminum	162 °C	Aluminum begins to lose strength
Fiberglass	350 °C	Fiberglass begins to deform

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Simple damage functions can be used to predict the physical/structural losses with sufficient accuracy. One example is the electrical grid where it is possible to model the damage due to wildfire to distribution networks and its assets power-substation, electrical lines, and towers by means of damage functions.

According to Fraser et al 2020, transportation infrastructure is vulnerable to postfire flooding, which can be many times larger than the level of flow that the original engineer considered when designing the infrastructure and depends on several factors associated to the drainage area.

An additional potential damage function can be related to the road visibility as determined by the PM10 concentration levels from smoke, according to Sfetsos et al 2021.

- **No Visibility (Road Should be Closed)**

  PMmean > 30 mg/m^3

- **Medium Visibility (Road Should be Closed)**

  10 < PMmean < 30 mg/m^3

- **Good Visibility (No Closure of Road)**

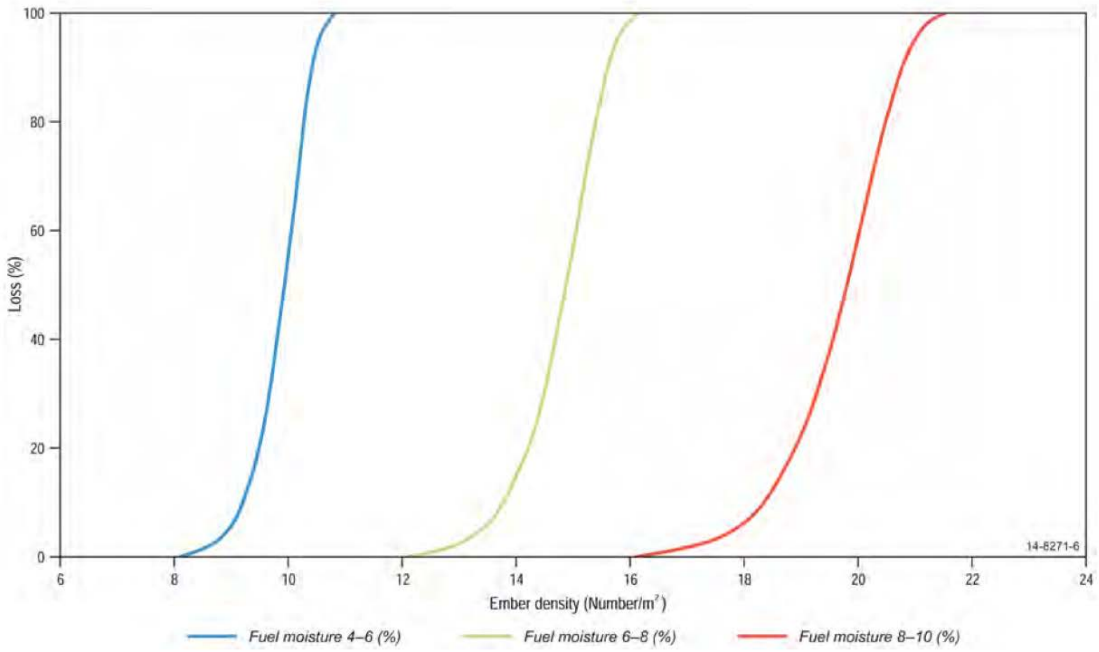
  PMmean mg/m^3

Wildfire damage functions for buildings

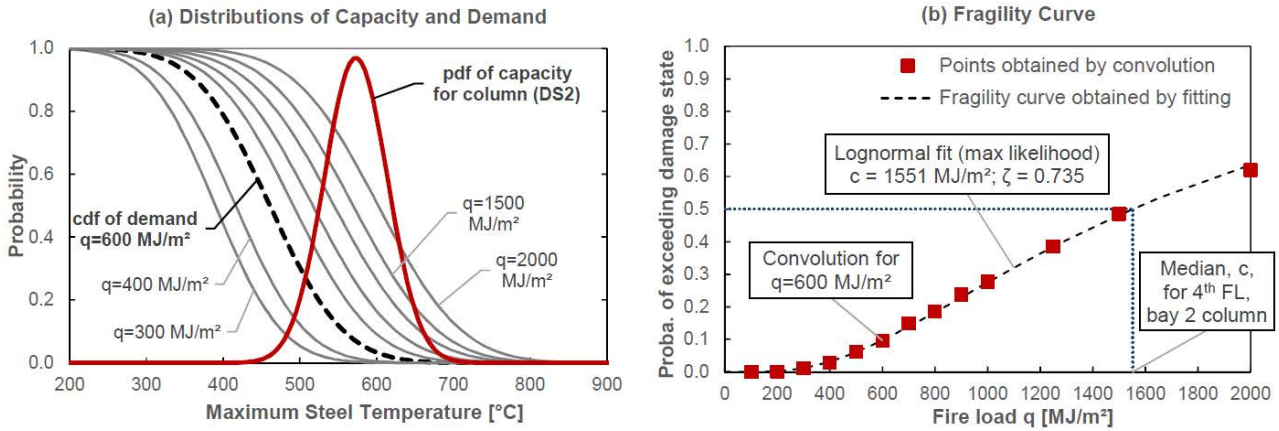
Damages to buildings due to forest fire can potentially be a significant failure to the structural safety and service ability of the building. House losses due to wildfires are mainly influenced by fire characteristics (fire intensity, spread rate, burning ember density), by house location, surroundings (defensible space, distance from forest, fuel accumulation), design and construction materials, and by fire suppression effectiveness" (Papakosta *et al.*, 2017).

According to Alhamadet al 2022, the current ACI and Eurocode codes discuss the level of the strength (normal, high) under fire without providing equations that cover the wide range of concrete types, the different heating rates, or even the effect of different cooling types and how they affect the post-fire properties of concrete. In addition, However, the design standards for a diverse composition and for different kinds of concrete such as FRC and RCA concrete are still not available (Malik et al 2021). The effect of fire on concrete is influenced by coarse aggregate types. More specifically, siliceous aggregate concrete retains approximately half its capacity at 650°C, whereas carbonate and light weight aggregate concrete exhibit near full capacity at 650°C (Chiang et al 2003, Edwards et al 1986). The thermal protection of reinforcing steel is critical; Based on testing, bars heated beyond 500ºC lose significant amounts of yield strength and ultimate strength (Chiang et al 2003, Edwards et al 1986).

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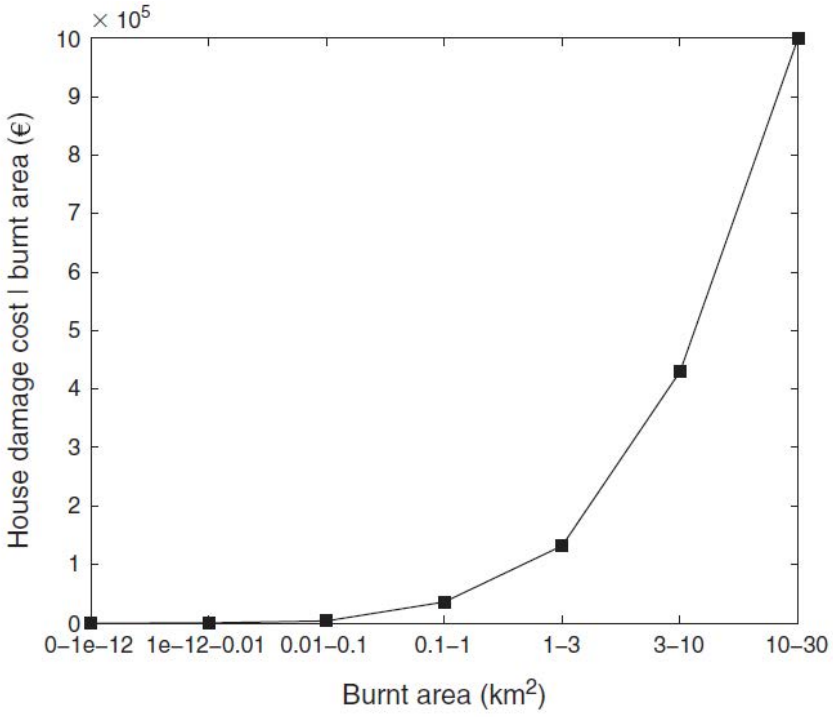


Vulnerability curves relating building loss (as percentage of its value) to the ember density for varying fuel moisture content [(Cechet et al., 2014)]



The fragility points are obtained by convolution of probability distribution function of damage state and complementary cumulative distribution function of demand (Gernay et al., 2015)

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Housing economic loss [€] conditional on burnt area [km²] estimated by Bayesian network (Papakosta et al., 2017)

Water system

Wildfires can be a source of Volatile organic compounds (VOCs) which, including benzene, could be seeping into the water system and circulate in drinking water through the deposition of smoke particles or through runoff in natural water resources (lakes and rivers). A water system loses pressure due to fire damage, then smoke, ash and gases can get sucked into underground pipes and circulated throughout a water distribution system (Proctor et al 2020). As mentioned in this study, VOCs are hypothesized to be derived from in-situ plastic pyrolysis and/or water or air contaminants from structures burning and/or vegetation burning being drawn into the distribution network. The following exposure limits have been defined from the federal government (U.S. Environmental Protection Agency [USEPA], 2018; USEPA, 2018; SWRCB, 2018a, 2019d) for several volatile organic compound (VOC) contaminants (e.g., benzene at 40,000 µg/L [Tubbs] and >2,217 µg/L [Camp]).

The basic principles of water treatment process design (Table 3) have been detailed by MWH (2005), who note that conventional water treatment processes are typically used to treat surface waters with high turbidity, color, or total organic carbon (TOC). Although treatment process selection, design, and operation are based on numerous factors that are not limited to source water quality, quality-based threshold values and ranges play a significant role in designing new or optimizing existing treatment processes (Emelko et al 2011).

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Key water quality thresholds associated with surface water treatment process selection and design (MWH, 2005)

Process	Turbidity (NTU)	Color (color units)	Dissolved Organic Carbon (DOC) (mg/L)
Conventional	high >20 NTU	high >20 c.u.	high >4 mg/L
Direct/Inline filtration	low ≤15 NTU	moderate-low ≤20 c.u.	low <4 mg/L
Microfiltration	low ≤10 NTU	moderate-low ≤10 c.u.	low <4 mg/L

Impact of wildfires on Infrastructure:

The following table describes the impacts on Infrastructure that are related to forest fires and smoke exposure:

Iimpacts on Infrastructure related to forest fires and smoke exposure

INFRASTRUCTURE	IMPACT
Energy and Power Sector	Directly damage transmission poles and other electricity infrastructure. According to Sakumoto et al 2003, the strength of steel is reduced to 0.5 at a temperature range from 500 to 600 °C and this is the point where steel transmission towers are not able to bear the design load. At this 420 °C the galvanizing increases with consequences for the corrosion prevention after the fire (Brandt 2003). This temperature is supposed to be reached after 10 min of fire exposure. Shut down the electricity transmission lines and produce power outages (Ward et al 2013, Sathaye et al 2012). Lines can be damaged simply by the heat of the fire, even if they are not burned directly. Conductors can become annealed or damaged and subsequently fail. Outage of a transmission circuit if it raises the ambient temperature of the air around the conductors above the line's operating parameters (Sunrise Powerlink Project, 2008)

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	Smoke and ash from fires can ionize the air, creating an electrical path away from transmission lines (Barbero et al 2020). Wooden pylons are submitted to fire front leading to their destruction (Smith 2014)
Oil & gas and chemical industries	Forcing the evacuation of industry employees causing production loss due to facilities being shut down. Threat of the industry exploration, production, transportation, storing and processing facilities Large-scale releases may pose serious water, soil and air contamination. Shutdown of the compressor station
Transportation	Fire, ashes and smoke because of wildfires are limiting visibility and restricting safety of transportation thereby. Reduced speed on roads. Operation is ceased, resulting in cascading effects on the rest of the network (road closure) (Habermann et al 2018) Heat extension, tracks can bend or buckle if the material is not heat-resistant. Possible suspension or reduce of flights because of the dense smoke of a wildfire nearby (aviation can be disturbed) Particulate matter is expected to damage constructions and technical equipment Affect railway infrastructure
Water system	Affect water infrastructure assets indirectly by increasing the volume of nutrients and debris transported by water and deposited in reservoirs and even reach treatment plants and distribution networks blocking pipes and affecting the lifespan of the assets (WRF 2013, EPA 2015) It is well known that wildfires can contaminate natural waters, including drinking water sources, with ash pollution and sediment (Emelko, Silins,

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	Bladon, & Stone, 2011; Smith, Sheridan, Lane, Nyman, & Haydon, 2011)

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Annex B: A124 – Economic impacts of fires: Selection of Papers from the Literature Review on Economic Impacts of Fire

Selected papers addressing natural capital, ecosystem services and other values

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003890.

Capital or socio-economic impact	Topic (reference-number)	Method
Natural capital		
Biodiversity	Value of charismatic species (Molina et al. 2019-1) Valuation of forest biomass fuel and associated environmental benefits (reduction on wildfire, pest, improved biodiversity etc.) (Susaeta et al. 2010-2) Public perceptions of socioeconomic and environmental benefits of woody biomass electricity production (Susaeta et al. 2010 - 3) Value measures that reduce impact of fires on marine and terrestrial biodiversity (Durán-Medraño et al., 2017- 4)	Contingent valuation method. Species valued as function of habitat recovery Choice experiment Choice experiment WTP analysis Choice experiment/
Timber	Fire impact on timber of Amazon by an ensemble of models (Oliveira et al., 2018 -5) Wood production analysis based on CBA (Ratknic et al.- 6) Timber and value change caused by climate change in Russia (Torzhkov et al. - 7) Fire impact on Timber NTFP and hunting in Spain (Molina et al., 2014 - 8) Timber vulnerability valuation as integration of economic damage and fire behaviour (Rodríguez y Silva et al., 2012 - 9)	Ecofire + FISC model + SImMadeira (timber rent) CBA Climatic model and market price analysis Climatic model and market price analysis Valuation of tangible asset based on method used by the Spanish Forest Service (Rodríguez y Silva et al., 2012b). Tangible assets valuation covering timber and non-timber resources combining USDA and National Fire Management Analysis System in Spain
Water (not many specific papers addressing monetary aspects of water	Post-fire hazards via source water contamination and mudslides (Robinne et al., 2020 - 10) Damage on intangible assets caused by fire and other hazards and	No valuation, but watershed governance analysis Revealed-preference and stated-preference methods

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values)	mitigation cost (Rogers, A.A., Dempster, F.L., Hawkins, J.I. et al., 2019 - 11) Water contamination after fire and mudslip/watershed risk management (Robinne et al., 2021 - 10) Interplay between fire, society and water (Kinoshita et al., 2016 - 12) Relations between fire, water quality and damage to society (Escobar, 2016 - 13) Damage on humans, infrastructures and indirect damage on water (Montagné-Huck et al., 2018- 14) WTP for the protection of watershed and its capitals provided (water quality, critical habitats, cultural areas) (Mueller et al., 2019-15)	(in particular: contingency valuation) - Values that are affected by natural hazards and their mitigation (Physical health; mental health, Ecosystems; Water quality; Recreation; Amenity, Safety; Cultural Heritage; Social disruption; Animal welfare) Review Review Review Review Choice experiment
Soil/soil erosion (no economic values)	Erosion and soil nutrient status after wildfires (Jhariya and Singh, 2021 - 16) Mobilization of toxic contaminant after fire (Joji Abraham et al., 2018 - 17) Debris flow following fire (Parise et al., 2017- 18) Landslide occurring after fire (Lainas et al., 2015- 19) Debris flow in burnt area in the Mediterranean and USA (Parise and Cannon, 2012 - 127) (Sarro et al., 2021- 20)	Analysis of soil - samples from 0–10 to 10–20 cm (high, medium, low, and no fire zone) Soil analysis before and after controlled burn Review Analysis of tipping point- landslide formation after rainfall Review
Carbon	Impacts of fire on carbon storage in relation to biomass consumption in Andalusia, Spain (Molina et al., 2019- 21)	flame length impact analysis, biomass consumption and economic valuation

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	Economic value of carbon storage and carbon releases over one century produced by fuel reduction (Ching-Hsun Huang et al., 2013- 22)	Value of carbon and avoided damages
Recreation	The impact of forest fires on recreation demand (Boxall & Englin, 2008- 23) Valuation of the susceptibility to fire of recreation activities in protected areas (Molina et al., 2019 - 24) Impact of fire on landscape value &recreation (Molina & Silva 2019 -25) Impact of wildfire on recreational values (USA) (Bawa- 26) Valuation of recreation in a Californian site. Hypothetical wildfire scenarios were employed (Sanchez et al., 2016 - 27) Evaluate how fires impact recreation and visitation by hikers and mountain bikers in New Mexico (Hesseln et al., 2003 - 28) Valuation of fire recreation susceptibility in Spain (Molina et al., 2019- 29) Impact of wild and prescribed fires on hiking and biking recreation in Montana (Hesseln et al., 2004 - 30) Observed visitor behaviour in the US National Park (Duffield et al., 2013 - 31)	Changes in recreation site choice. Revealed Preference and Stated Preference (RP-SP). GIS analysis + travel cost method (TCM)+vegetation resilience + fire simulation Travel cost and depreciation value of landscape/ Stated and revealed preferences Choice experiment Travel cost method Willingness to pay, onsite stated preference survey based on hypothetical wildfire scenarios Travel cost + stated preference method (intended trips) Travel cost
Forest ecosystem	Social attitude towards forest values and protected areas (Lorek & Lorek, 2021 - 32) Fire regulation capacity of abandoned ecosystems (Ângelo Sil, 2019- 33) Valuing resilience of forest after fire (Tong Wu and Yeon-SuKim, 2013 - 34) Damage to trees and ecological functions in Serbian forest (Predrag Aleksić et al., 2009-35) WTP for the protection of watershed and its capitals provided (water	WTP survey Landscape simulation +market value of timber, NTFP Inclusive Wealth Risk/Ecological and economic damages to forest Choice experiment

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	quality, critical habitats, cultural areas) (Mueller et al., 2019- 15) Loss of Ecosystem services from bushfire in Australia (Kamaljit K.Sangha et al. 2020 - 36) WTP for forest fire management externalities (biodiversity, access for recreation, carbon sequestration and burned areas) (Varela et al., 2016- 37) Fire damage to agroforestry (crops/infrastructure) in Tuscany (Italy) (Fagarazzi et al., 2021 - 38)	Replacement Cost (RC) for assessing the flow of lost ecosystem services Choice experiment/ compensating surplus between scenarios Review: Ecos. services; TCM for recreation; Faustmann formula for timber
Health externalities	Prenatal exposure to fire pollution and adult height (Indonesia) (Tan-Soo & Pattanayak, 2019- 39) Health cost of fire in Los Angeles (Richardson et al., 2012 - 40) Review on cost, health damage and WTP fire mitigation (Ikuho Kochi et al., 2010- 41) Health cost (as respiratory diseases) of wildfire smoke (Jones, 2018- 42) Development of an air quality benefit transfer tool, the US EPA benefits mapping and analysis program-community edition (BenMAP-CE), (Jones et al., 2015- 43) Comparison cost of illness and WTP for reduced smoke exposure (Richardson et al., 2013- 44) Elicitation of willingness to pay to address deteriorating visibility conditions arising from wildfires (Haider et al., 2019- 45)	Social cost benefit analysis / panel data regression Willingness to pay for a reduction in one wildfire smoke Review WTP estimated by the life satisfaction approach Benefit transfer Comparison of cost of illness and WTP from stated preferences (CVM) Choice experiment
Agriculture	Impact of wildfires on grassland for swine production in Spain (Molina et al., 2011- 46) Damage assessment in palm oil plantation (+ pollution+carbon) (Putra et al., 2020 - 47) Fire damage to agriculture (crops/infrastructure) in Greece (Stougiannidou et al. 2020 - 48) Economic impacts to agriculture in Chapada (Brasil) (Lara et al. - 49)	Use of market data. Analysis of carrying capacity. Fire simulation of impacts Net value + recovery from damage +prevention Review: Damages+ prevention cost +suppression and indirect cost Direct interviews +evaluation of damages

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	Economic effect of fire on agriculture and forestry (Korea) (Kwon & Kim, 2014 - 50)	Production function (CobbDouglas)
Hunting	Socio-economic effects of forest fires on hunting (Zamora et al., 2010- 51)	Market price analysis integrated with sustainable assessment of catches before and after fire. Reduced catches are estimated according to fire severity
Build capital House /infrastructures	Effect of fire on house property price in Los Angeles (Mueller & Loomis, 2014 - 52) Damage on houses caused by rockfall (Spain) (Sarro et al., 2021 - 20) Effect of fire on expected transaction of houses in Colorado (Kiel et al., 2018 - 53) Loss prediction applied to housing in Cyprus (Papakosta et al., 2017- 54) Influence of proximity to and visibility of wildfires on home values (Stetler et al., 2010 - 55)	Hedonic price model Review difference-in-difference approach Bayesian network analysis hedonic price framework
Other socio-economic impacts *Valuing decision making*	Fire forces a poverty trap in the Amazon (Cammelli et al., 2020 - 56) Wildfire and growth and employment in USA (Nielsen-Pincus et al., 2014- 57) Effect of fire on health and supply chain in US (Wang et al., 58) Subjective perception of fireshed damage in Lebanon (Mitri et al., 2018 - 59) Management options for ranchers in Nevada following a fire (Richardson et al., 2013- 60) Impact of 6-week fire in Florida in 1998 (Butry et al., 2001- 61) Bushfire management in Australia (Ganewatta and Handme, 2006- 62) Aboriginal fire stisk farming model (Wilman, 2013- 63)	Interview+remote sensing+production data data on wildfire + county-level employment/panel regression model regional IO model + dose-response (C-R) function survey on socio-economic perception of wildfires FLIPSIM, a firm level simulation model Change in cost and expenditure before/after fire Estimate the total social economic cost and benefits Analysis of net benefits from optimal controlled burning Choice modelling and focus groups

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	WTP for woody biomass energy stemming from thinning for reduced wildfire risk - energy generation, forest health and air quality were incorporated into the social preference survey (Campbell et al., 2016- 64) WTP for implementing prescribed burning and reduce fire hazard in the USA (Shrestha et al., 2021 - 65) Analysis of decision making of fire managers based on risk to housing and watershed resources (Calkin et al., 2012- 66) Intensity of salvage logging and forest diversity (Graham, 2004- 67) Analysis of scenarios management through WTP for the provision of ES (Gorriz-Mifsud et al., 2016- 68) Preferences for wildfire prevention policies in Spain (Allo & Loureiro, 2020 - 69) Participants' willingness to pay for fuels management programs (prescribed burning, thinning) (Walker et al. 2007- 70) Value emerging from three different post-fire management strategies (Leverkus & Castro, 2017- 71) Cost of wildfire to health, transport disruption and tourism in South-eastern Asia -recreation (Lin et al., 2017- 72)	Contingent valuation method Choice experiment Review of cost and benefit of salvage logging opportunity cost, willingness to pay, payment for ecosystem services, choice experiment survey Literature review, discrete choice experiment, conversations with experts and the public (400) contingent valuation method replacement cost method (economic valuation), ecosystem services framework Continent valuation
Landscape	Spatial vulnerability for landscape in Spain (Molina et al., 2017- 73) Impact of fire on landscape value/recreation (Molina & Silva, 2019- 25) Subjective perception of landscape change after wildfire (Chile) (Oieda et al - 74)	CVM+fire behaviour+forest resilience travel cost and depreciation value of landscape semi structured interview

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	Socio-economic landscape susceptibility to fire in Chile (Molina et al., 2018- 75) Economic value of landscapes and integrates social, economic and ecological aspects (Molina et al., 2016- 76)	Landscape value by CVM and net-value change (NVC) or depreciation analysis based on people statements for different landscape Contingent valuation, preference, GIS mapping, DELPHI method
Social capital	collective actions enforce the rules for fire risk mitigation in Nepal (Sapkota et al., 2015- 77) Volunteering effect on fire risk management in the Med area (ElenaGórriz-Mifsud et al., 2019- 78) Role of community fireguard groups in fire management/Australia(MacDougall et al., 2014 - 79) Social capital and collective action in fire mgt. in Indonesia (Jalil et al., 2021- 80) Bonding in Oregon communities to mitigate fire risk (Jacobs and Cramer, 2020- 81) Analysis of network/ ties in Oregon for fire management (Fisher and Jasni, 2017 - 82) (Jacobs and Cramer, 2017- 83) Fire service performance and social capital in USA (Andrews and Brewer, 2010- 84)	Primary +secondary data on community participation Lit review+Survey on locals+regression model Focus group discussions Informant interviews Questionnaire survey to residents Interview/ descriptive statistics Social capital index/OLS regression
Human capital – training education	Improve knowledge and use of remote sensing for disaster mgt (Hazarika et al., nd- 85) Wildfire prevention education in Florida (L.A. Hermansen-Baez et al., 2011- 86) GIS, policy makers and stakeholders' engagement for fire management plan in Spain (Tabara et al., 2003- 97) Risk management and fire prevention strategy to reduce ecological and social damage of fire in the Great basin Region US (Narayanan et al.,	Training on using remote sensing models Education campaign GIS technologies, simulation computer program FARSITE on fire propagation, dialogic participation Two days forum: discussion of causes and recommendation

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	2009 - 88) Participatory land and forest conservation/rehabilitation initiative in Indonesia (Hiratsuka et al., 2019- 89) Community strategy, collecting action for Himalayan Forest (Chauhan et al., 2021- 90) Community engagement in Seychelles for forest management strategies (Etongo, 2021 - 91) Role of network in the West US to facilitate prescribed burning (Huber-Stearns et al., 2021-92)	Participatory approaches community meetings, training and workshops to educate people to sustainable forest management Workshops and household survey Interview with federal land management agencies and cooperative actors

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Annex C: A124 – Methods for valuing and mapping agricultural values at the European Territory scale

Forest land values

The value of timber land expressed in euros per hectare (€/ha) is reported at national scale in the European Union in 2021 currency. It is calculated by taking the growth rate of timber expressed in m3/ha in in each country provided by EUROSTAST (https://www.eea.europa.eu/data-and-maps/indicators/forest-growing-stock-increment-and-fellings-3/assessment) and correcting it by the stumpage price of softwood (€ 70/m3 in June 2022) (https://www.forestresearch.gov.uk/tools-and-resources/statistics/statistics-by-topic/timber-statistics/timber-price-indices/) to get the annual value of the growing stock.

A margin of 5% is used to calculate the net annual revenue (https://www.forest2market.com/blog/a-complete-look-at-logger-expenses), expressed in €/ha per year. A capital value of the asset, expressed in €/ha, is calculated assuming that the net revenue is accrued in perpetuity by dividing the net revenue by the rate of capitalisation of 4%. This can be assumed an average rate (values from 2 to 6% are also used), depending on the condition of risk (https://www.farmlend.com/article/cap-rate-calculating-rate-of-return). We assume a condition of medium-high risk that gives the opportunity to estimate an average-upper bound value of timber likely to be completely lost after wildfires.

To calculate more specific value of the net change (resilience) of timber over time from the spread of wildfire until the end of the rotation period, it is necessary to calculate the net present of the annual revenue expressed in €/ha per year using the equation 1 reported in the chapter 7 of the manuscript.

For the spatial representation of timber values (Figure 1), economic values were linked to the NUTS 1 layer of the European Union using its Geocodes. The values corresponding to the capital value expressed in euros per hectare were reported in a raster file that was then clipped with the forest areas represented in the fuels map made within the FirEURisk project (Aragoneses et al., 2022). The selected categories of the fuel map correspond to the following Forest classes:

- 1121 Deciduous broad leaf open forest
- 1122 Deciduous broad leaf closed forest
- 1211 Needleleaf Evergreen Open
- 1212 Needleleaf Evergreen Closed
- 1301 Mixed Open Forest
- 1302 Mixed Closed forest

Fruit grove values

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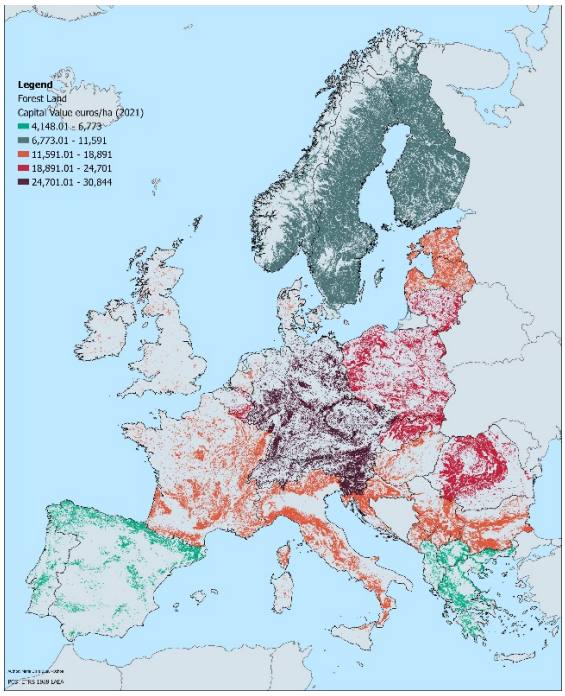


Figure 28: Representation of timber net revenue for 2021 in euros/ha

Values of fruit trees in €/ha were derived by EURSTAT data based on fruit production and revenue for the year 2017 (https://ec.europa.eu/eurostat/statistics-explained/SEPDF/cache/53634.pdf; Statistics | Eurostat (europa.eu). A profit margin of 20% has been used (*Badiu et al. 2015, Evaluation of Economic Efficiency of Apple Orchard Investments, Sustainability, 2015, 7, 10521-10533; doi:10.3390/su70810521*) to get the net annual revenue in €/ha per year, while a capitalization rate of 4% has been used to calculate the capital value of the asset in €/ha.

Fruit groves capital value is reported in Figure 2. Values were first spatially represented at NUTS 1 scale; then the capital value in euros per hectare was rasterized and cut according to the presence of fruit groves from Corine Land Cover 2018 class “Fruit trees and berry plantations”. Since the values refer to 2017, we have multiplied the values by a CPI of 5% to convert them into 2021 prices.

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Figure 29: Representation of fruit groves net revenue for 2021 in euros/ha

Olive grove values

Olive trees value is reported at scale of nation in 2021 currency. This is built on EURSTAT data on olive production for the period 2011 to 2021 (https://ec.europa.eu/eurostat/databrowser/view/TAG00122/default/table).

An average price of € 0.45/kg, observed in 2021 by the Italian Institute for food market (ISMEA), is used (https://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/652) to convert production in revenue. This value is applied to all olive producer countries.

Revenue has been divided by the area of olive plantations per country as reported by EUROSTAT (https://ec.europa.eu/eurostat/databrowser/view/orch_olives2/default/table?lang=en) and corrected for the cost of managing olive groves (€ 500/ha according to ISMEA). An interest rate of 3% has been used to calculate the capital value of olive groves.

Olive groves capital values (Figure 3) were spatially represented by merging economic values with the NUTS 1 layer at the national level of the European Union. The capital value in euros per hectare was rasterized and cut according to the presence of olive trees from Corine Land Cover 2018. For those values missing in the tables, the average value corresponding to the European Union was used.

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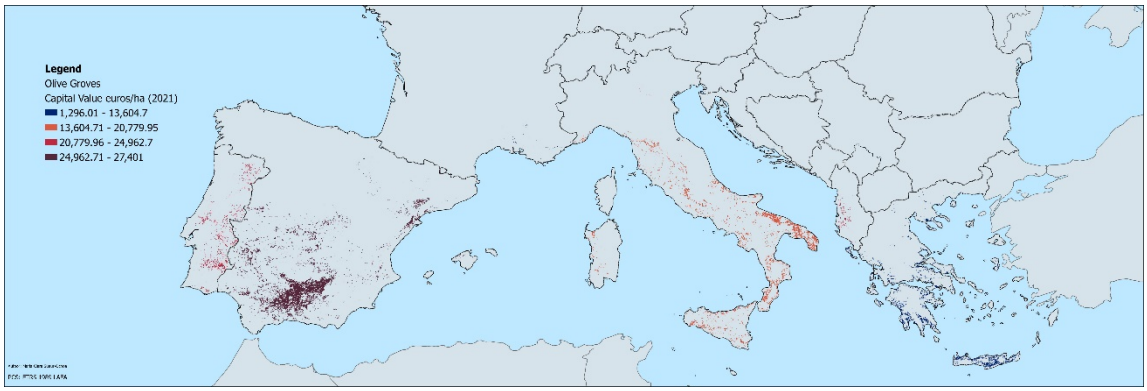


Figure 30: Representation of olive groves net revenue for 2021 in euros/ha

Vineyard values

Values of vineyard were reconstructed at scale of nation and NUTS2 (according to the classification provided in 2010) building on EUROSTAT data. Production of wines in hectolitres, available at https://ec.europa.eu/eurostat/databrowser/view/VIT_AN7$DEFAULTVIEW/default/table, and areas of vineyard production, available at https://ec.europa.eu/eurostat/databrowser/view/VIT_AN5$DEFAULTVIEW/default/table

are reported for the year 2007 and 2008 at NUTS2 level (according to the 2010 classification).

We use economic value for wine provided by ISMEA in 2021, with average price per litre of unbottled wine of € 1.5 (https://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/2603), as also confirmed by other sources (*Dimitrova and Dimitrov, 2021. Annual changes in the prices of table grapes and price margins in the supply chain. scientific papers series management, Economic Engineering in Agriculture and Rural Development Vol. 21, Issue 1, 2021 PRINT ISSN 2284-7995, E-ISSN 2285-3952*). A profit margin of 25% is used to calculate the net annual revenue of a vineyard (assuming an average cost of depreciation and maintenance of € 4,000 per ha – http://www.inumeridelvino.it/2014/02/il-costo-di-conduzione-della-vigna-e-potenziale-riduzione-studio-camera-agricola-di-bordeaux.html#:~:text=Il%20costo%20totale%20di%20conduzione,chimica%20ma%20molte%20pi%C3%B9%20lavorazioni).

A capitalization rate of 10% is used to calculate the capital value of the vineyard, expressed in €/ha (https://blog.vinfolio.com/2022/02/25/what-returns-should-you-expect-from-your-wine-investment/#:~:text=Since%201988%2C%20investment%2Dgrade%20wines,about%2010%20percent%20per%20year).

Vineyard capital value in the study area (Figure 4) was spatially represented by merging economic values with the NUTS 2 layer at regional level of the European Union. The capital value in euros per hectare was rasterized and cut according to the presence of vineyard from Corine Land Cover 2018. For those values missing in the tables, the average value corresponding to the European Union was used.

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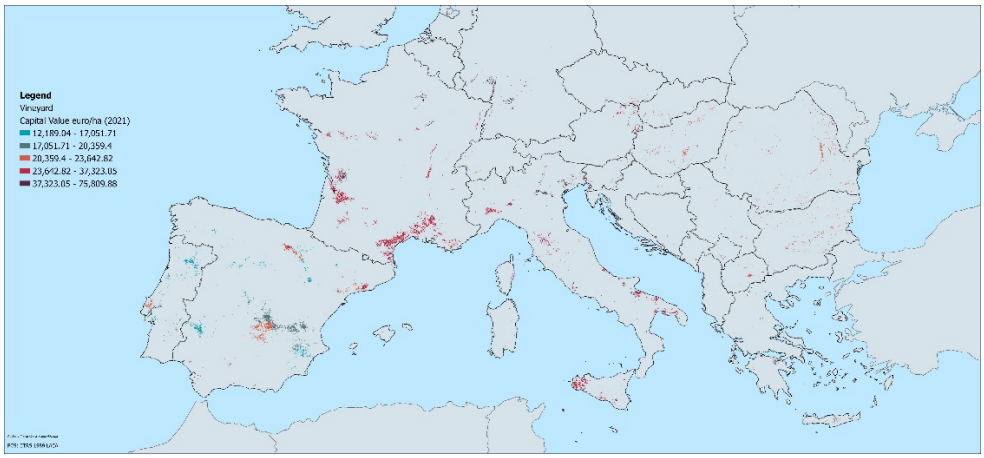


Figure 31: Representation of vineyard net revenue for 2021 in euros/ha

Livestock values

Cattle

Eurostat reports for the NUTS 2 region the number of heads up to 2016 (https://ec.europa.eu/eurostat/databrowser/view/EF_LSK_MAIN__custom_3144197/default/table) but not the value of this asset.

Considering the impossibility to discriminate between different types of cattle, we consider for this report the value of store cattle.

Average value for the whole EU territory is assumed by considering values from different countries. For instance, the average price of a cattle in the UK in 2021 was GBP 1,600 (https://ahdb.org.uk/dairy-cattle-rearing-calf-prices).

According to ISMEA, the market price of a life head per kg In Italy, was approximately € 3.4 in 2022 (https://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/722).

A similar price is reported by the observatory of agricultural price for the EU agricultural product, where the average price in 2022 was close to three euros per kg (€ 3/kg) (https://agriculture.ec.europa.eu/system/files/2022-08/beef-vi22-30.pdf).

Assuming an average weight of 600 kg per head (weight that can be achieved in 1 year), the value of a store cattle per head is approximately € 1,800.

More difficult was to retrieve information about the cost of cattle management. In Italy, and for the 2016 year, the cost of management was approximately € 2.50 per kg (https://informatorezootecnico.edagricole.it/bovini-da-carne/ismea-nei-vitellone-costi-non-coprono-spese/). Correcting for inflation (nearly 10% higher today than 2016 (https://tradingeconomics.com/euro-area/consumer-price-index-cpi#:~:text=Consumer%20Price%20Index%20CPI%20in%20Euro%20Area%20is%20expected%20to,macro%20models%20and%20analysts%20expectations), this is equivalent in 2022 euros to € 2.75/kg. Therefore, a bovine of 600kg average weight has a cost of approximately € 1,650.

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The average net revenue per head per year is assumed to be € 150. The spatialization of this variable was carried out by multiplying the number of cows published by the FAO by € 150.

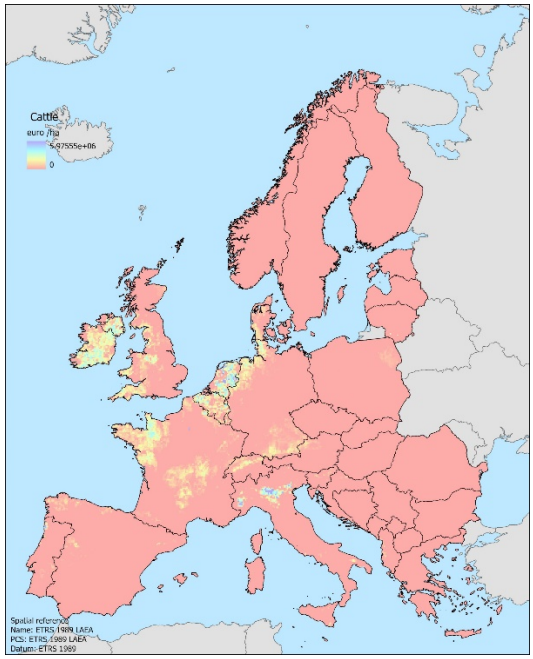


Figure 32: Representation of the average cost of cattle in euros/ha

Sheep

Eurostat reports for the NUTS 2 region the number of heads up to the year 2016 (https://ec.europa.eu/eurostat/databrowser/view/EF_LSK_MAIN__custom_3144197/default/table).

Cost of buying a sheep is about € 200. The cost of rearing a sheep is on average GBP 60 per ewe for the previous 12 months in the UK (https://www.cafre.ac.uk/2022/04/21/managing-rising-costs-on-sheep-farms-plan-ahead-to-remain-profitable-with-this-years-lamb-crop/). Similar values are recorded for the USA market where the cost of management is about US$ 60 per ewe (https://familyfarmlivestock.com/raising-sheep-for-profit-lets-look-at-some-numbers//).

We assume a cost of € 70 per head in our calculation with revenue per head in the order of € 3 to 4 per kg (https://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/817). Assuming an average weight of kg 50, the gross revenue per head is in the range € 150 to 200 per head. We assume that on average the net revenue per sheep can be approximately € 100 per head.

The spatialization of this variable was carried out by multiplying the number of sheep published by the FAO by the average value as above calculated.

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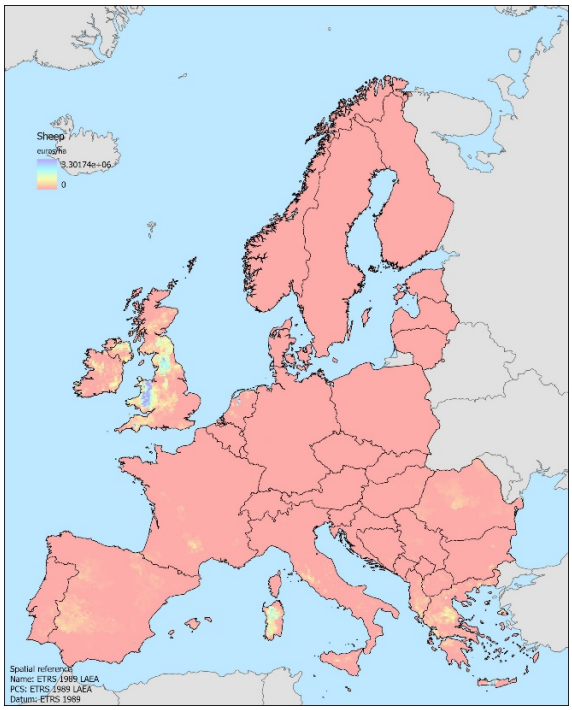


Figure 33: Representation of the average cost of sheep in euros/ha

Property values

Value of properties are expressed in €/square meter in 2021 currency. Because of the lack of availability of database reporting value of properties with a certain granularity, we have aggregated information at national scale with detailed maps of local GDP assuming a linear relation between the value of a property and the income of the geographic zone where the asset is located.

We calculated value of property multiplying the national average price of properties reported outside city centres by the website Numbeo for all the European countries (https://www.numbeo.com/property-investment/) and corrected by the ratio between the local and national GDP.

To map the capital value of property (Figure 7), we first used a local 2015 GDP layer (Kummu et al., 2020) produced by integrating GDP per capita (expressed in purchase power parity) with the gridded population data available from the Global Human Settlement (GHS). We divided the local GDP value by the national 2021 GDP of each country (corrected in 2015 values by consumer price index), and then multiplied the resulting layer (GDP ratio) by the spatialization of the property value at the national level for each country. Property values were provided by Numbeo in dollars and converted to euros by multiplying them by the 2021 reference exchange rate (0.8458).

NOTE: the weblinks proposed in the text were consulted between June and July 2022.

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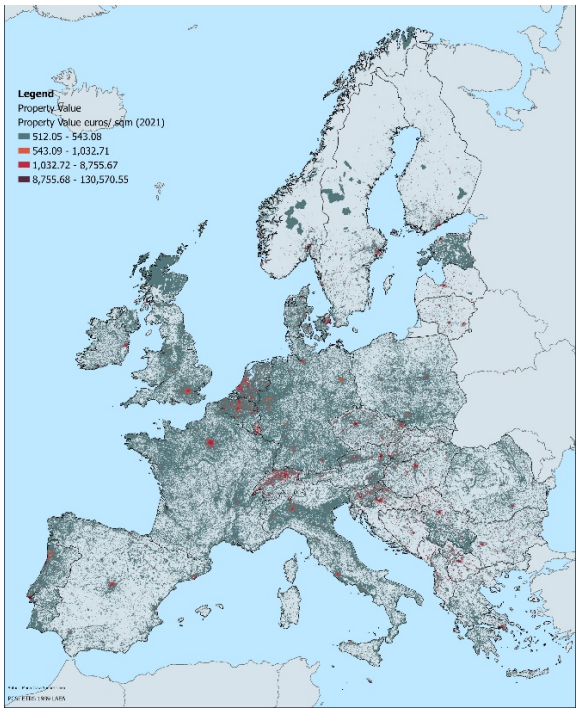


Figure 34: Representation of value of property in Europe for 2021 in euros/sqm

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Methods for valuing and mapping ecological services at European Territory scale

Carbon sequestration

We used maps already produced by the JRC and reported in the INCA platform. For detailed information on analysis and methodology we suggest referring to the INCA Platform website: https://ecosystem-accounts.jrc.ec.europa.eu/

We report values in the band 4 corresponding to monetary values referring to the year 2018 with min value of 1.1104743480682 and max value of 28398.720703125. All values are expressed in euros per Km2 computed using the market rate of carbon emissions from energy use. For our purposes, we have changed the units from euro per km2 to euros per hectare and multiplied the original value by 1.05 to correct for the current inflation based in the euro zone.

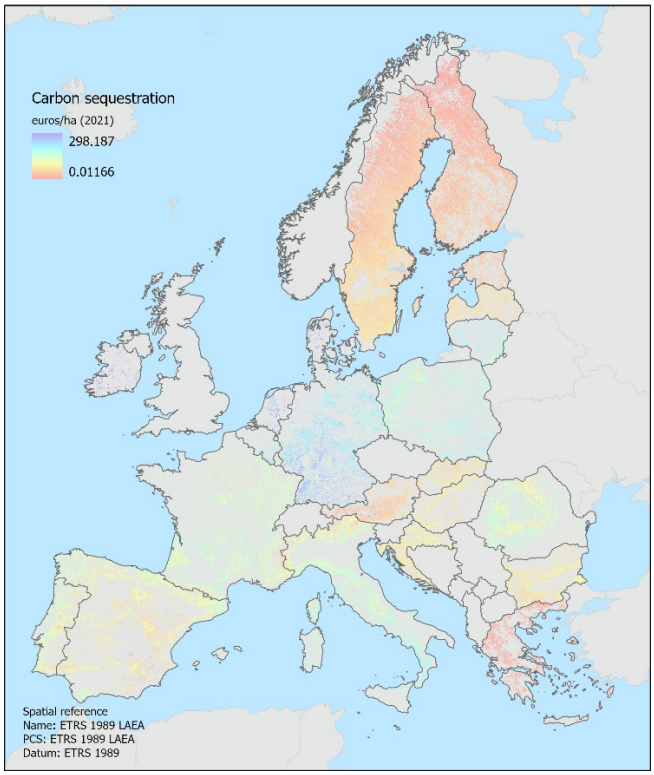


Figure 35: Representation of monetary value for carbon sequestration in euro/ha

Crop pollination

We used maps already produced by the JRC and reported in the INCA platform. For detailed information on analysis and methodology we suggest referring to the INCA Platform website: https://ecosystem-accounts.jrc.ec.europa.eu.

We used Band 4 corresponding to monetary values measured in the year 2018 with min value: 0 and max value: 149184.18630484 expressed in euros per km2. The value has been computed starting from the pollinator-dependent crop production covered by pollination service and by disentangling the contribution of the ecosystem service.

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For our purposes, we have changed the units to hectares and the consumer price index has been used to convert.

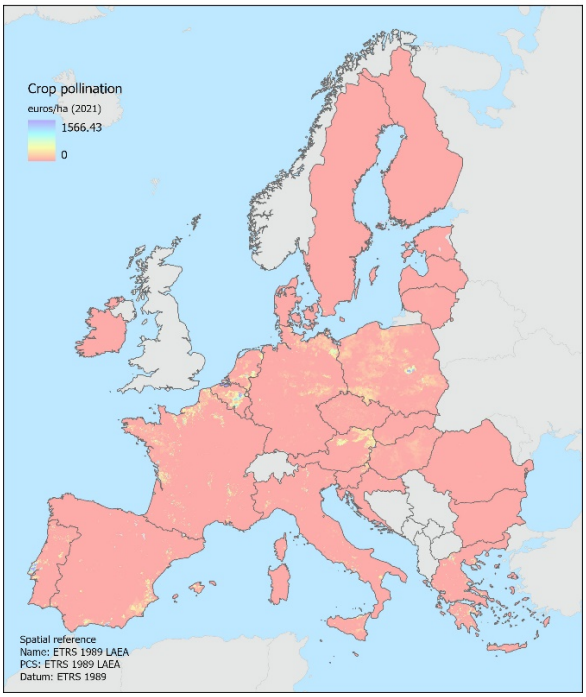


Figure 36: Representation of monetary value for crop pollination in euro/ha

Flood Control

We used maps already produced by the JRC and reported in the INCA platform. For detailed information on analysis and methodology we suggest referring to the INCA Platform website: https://ecosystem-accounts.jrc.ec.europa.eu.

We used Band 4 corresponding to the monetary values reported in the year 2018 with min value: 0 and max value: 472250048. The raster values proposed by JRC are multiplied by 1000 to convert them to integer. In order to obtain the original values, the raster values has been divided by 1000 and then converted in euros per ha. All results provided in the study (maps) refer only to EU-26, excluding Cyprus, Malta, and some regions in Croatia, Bulgaria and Finland.

The monetary value of flood control service was quantified with the avoided damage cost method building on damage cost function (expressed in EUR/m2), a relationship between damage per class (e.g., residential buildings, commercial buildings, etc.) per different levels of water depth (expressed in meter) and averaged according to different flood return probability (from 10 to 500 years). Damage cost functions vary among countries based on the Gross Domestic Product (GDP) per capita. For our purposes, we have changed the unit of measure from euro per km2 to euros per hectare and an inflation rate of 5% applied (eurozone inflation from 2012 to 2021 according to the consumer price index in the eurozone).

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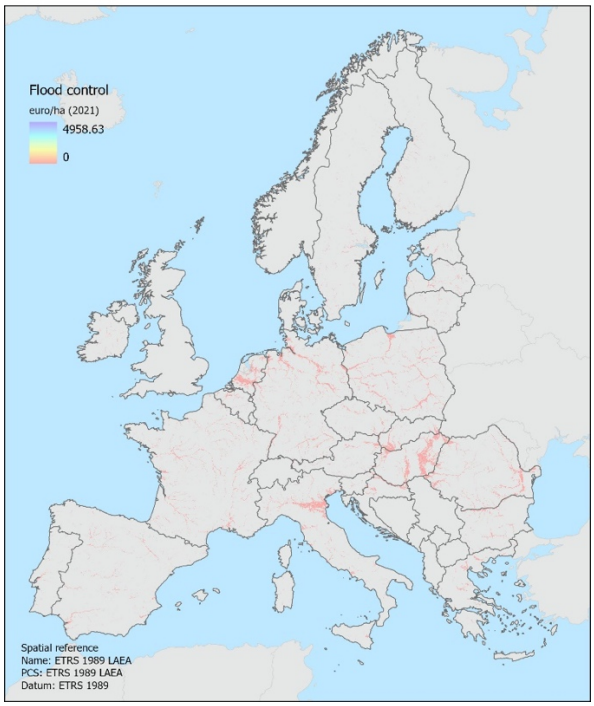


Figure 37: Representation of monetary values for flood control value in euro/ha

Soil retention

We used maps already produced by the JRC and reported in the INCA platform. For detailed information on analysis and methodology we suggest referring to the INCA Platform website: https://ecosystem-accounts.jrc.ec.europa.eu.

We used band 4 corresponding to the monetary value in the year 2018 with min value: 122 and max value: 10094756. The raster values proposed y JRC are multiplied by 1000 to convert them to integer. In order to obtain the original values, the raster values has been divided by 1000 and then converted in euros per ha.

Description: monetary value of soil retention services was expressed in Euro per hectare estimated using the cost replacement method. It is assumed that the benefit of soil retention can be quantified by the cost of replacing the nitrogen lost by erosion through acquisition in markets. For our purposes, we have changed the units from euros per km2 to euros per hectare and the average consumer price index between 2018 and 2021 used to correct valeus in 2021 currency.

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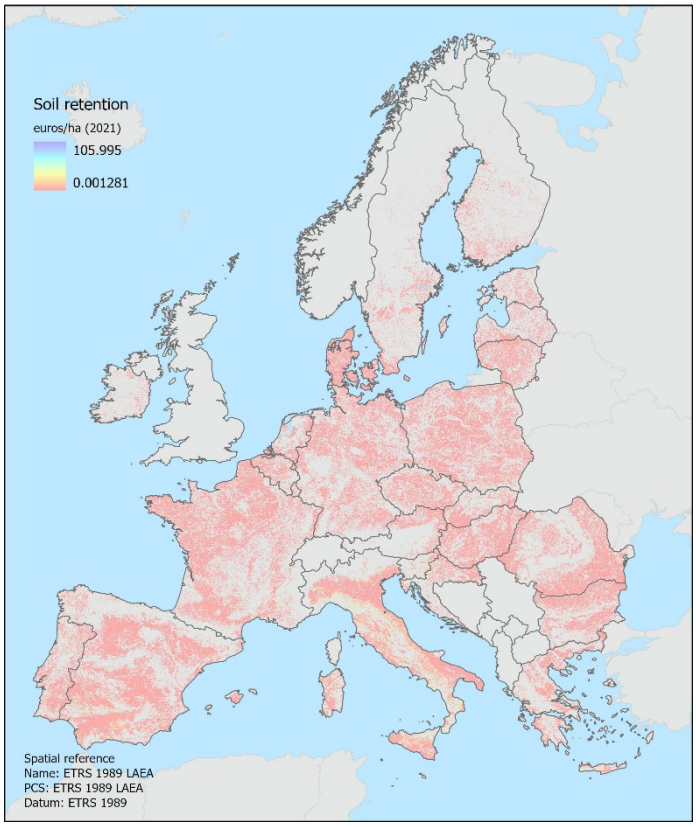


Figure 38: Representation of monetary value for soil retention in euro/ha

Water purification

We used maps already produced by the JRC and reported in the INCA platform. For detailed information on analysis and methodology we suggest referring to the INCA Platform website: https://ecosystem-accounts.jrc.ec.europa.eu. For information on the methods used refer to the following publications: *La Notte, A., Vallecillo, S., Bendito-Garcia, E., Ferrini, S., Grizzetti, B., Rega, C., Czuck, B., Zurbaran, M., Maes, J. 2021. Ecosystem service accounting. Part III- Pilot accounts for habitat and species maintenance, soil retention and water purification. JRC Technical Report*.

We used band 2 corresponding to the monetary values provided for the year 2012. The raster values proposed by JRC are multiplied by 1000 to convert them to integer. In order to obtain the original values, the raster values have been divided by 1000 and then converted in euros per ha. Conversion in 2021 monetary value is made by applying an inflation rate of 5% to convert 2012 in 2021 currency using the average consumer price index in the eurozone. Economic valuation is based on the replacement cost method. This is the cost necessary to build constructed wetlands able to prevent the load from entering water bodies and remove the excess of nitrogen.

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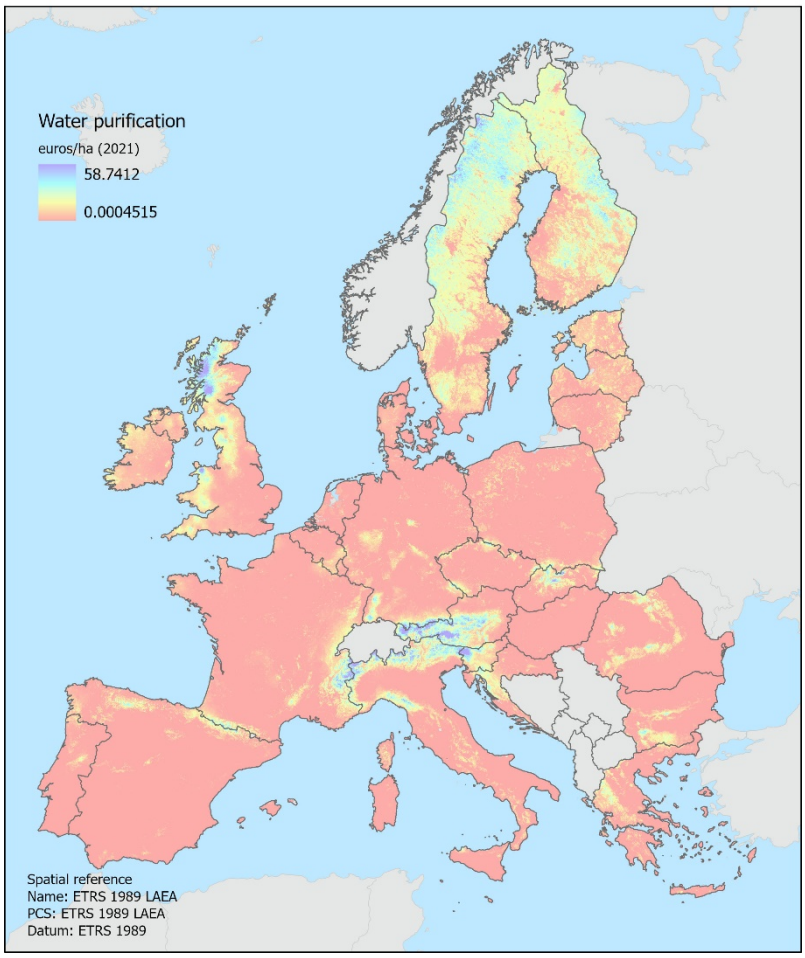


Figure 39: Representation of monetary value for water purification in euro/ha

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