

Essays at the intersection of wildfire management and environmental policy: state of the art in mediterranean-climate regions, and impacts and synergies in Portugal

Renata Martins Pacheco

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Professor of Faculdade de Engenharia da Universidade do Porto

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Abstract

Wildfires are an increasing concern worldwide, causing substantial social, economic, and environmental impacts, and are expected to become more prevalent in the future due to climate change. This situation is especially relevant in mediterranean-climate regions, present in all the five continents of the world, in which fire is a natural component of the environment and perhaps one of the most significant evolutionary forces. Within Europe, Portugal is the country with the highest number of wildfires and the second with more burnt area, majorly impacting the nation in social, economic, and environmental terms. To address this situation, Portugal has recently created new environmental policies that deal with climate change, fire management, and biodiversity conservation through payment for ecosystem services schemes. In this setting, this thesis provides an analysis of the current state of knowledge on wildfire management practices in mediterranean-climate regions to characterize the aspects that need to be further studied. In this stage, the results of the systematic mapping process indicated that some aspects of wildfire management had been thoroughly studied but unevenly across all the globe. Moreover, there is a lack of multidisciplinary work incorporating expert knowledge in the literature. For this reason, the next stage of the work was more specific, focused on Portugal. The most prominent ecosystem services impacted by wildfires in the country were characterized using multiple research methods through a triangulation approach, including academic, governmental, and specialists' perspectives. In this phase, it stood out that the impacts most addressed by the government and literature are more linked to provisioning services related to the flora. The specialists, however, indicated that all forest services are impacted, and not all have policies to address them, as is the case of the climate regulation service. In this sense, through a carbon sequestration perspective, an economic analysis using a payment for ecosystem services method was performed to evaluate the newly established carbon taxation in Portugal as a means to incentivize forest restoration and fire management measures. The results indicate that these policies are individually cost-effective and can work synergistically in addressing wildfire impacts, namely carbon sequestration, as is recommended by development agendas, like the Sustainable Development Goals. The findings and analysis framework employed in this study might be helpful for other countries, especially in the Mediterranean Basin.

Resumo

Os incêndios florestais são uma preocupação crescente em todo o mundo, causando impactos sociais, económicos e ambientais substanciais, e espera-se que se tornem mais prevalentes no futuro devido às alterações climáticas. Esta situação é especialmente relevante nas regiões de clima mediterrâneo, presentes em todos os cinco continentes do mundo, onde o fogo é uma componente natural do meio ambiente e talvez uma das forças evolutivas mais significativas. Na Europa, Portugal é o país com maior número de incêndios florestais e o segundo com maior área ardida, com um forte impacto social, económico e ambiental. Para fazer face a esta situação, Portugal criou recentemente novas políticas ambientais nos domínios das alterações climáticas, gestão de incêndios e conservação da biodiversidade por meio de esquemas de pagamento por serviços ecossistémicos. Neste contexto, esta tese apresenta uma análise do estado atual do conhecimento sobre as práticas de gestão de incêndios florestais em regiões de clima mediterrâneo para caracterizar os aspectos que carecem de aprofundamento. Nesta fase do trabalho, os resultados do processo de mapeamento sistemático indicaram que alguns aspetos da gestão de incêndios florestais foram amplamente estudados, mas de forma desigual em todo o globo. Verifica-se ainda na literatura uma carência de trabalhos multidisciplinares que incorporem conhecimentos de especialistas. Por esta razão, a etapa seguinte do trabalho foi mais específica, focada em Portugal. Os serviços ecossistémicos mais proeminentemente afetados pelos incêndios florestais no país foram caracterizados por meio de vários métodos de investigação, através de uma abordagem de triangulação, incluindo perspectivas académicas, governamentais e de especialistas. Nesta fase, destaca-se a verificação de que os impactos mais abordados pelo governo e pela literatura estão mais associados aos serviços de aprovisionamento, relacionados com a flora. Os especialistas, no entanto, indicaram que todos os serviços florestais são afetados, e nem todos possuem políticas públicas de apoio, como é o caso do serviço de regulação climática. Neste sentido, assumindo a perspetiva do sequestro de carbono, foi realizada uma análise económica por meio de um método de pagamento por serviços ecossistémicos para avaliar a nova taxa de Adicionamento sobre as emissões de CO₂ em Portugal, como meio de incentivo à recuperação florestal e medidas de gestão de incêndios. Os resultados indicam que essas políticas são individualmente eficazes em termos de custos e podem funcionar sinergicamente na abordagem dos impactos dos

incêndios florestais, nomeadamente o sequestro de carbono, conforme recomendado pelas agendas de desenvolvimento, como os Objetivos de Desenvolvimento Sustentável. Os resultados e a estrutura de análise deste estudo podem ser úteis para outros países, especialmente na Bacia do Mediterrâneo.

There is a difference between progress and technology.
Progress benefits mankind. Technology does not necessarily do that.

Nikola Tesla

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Contents

1	Introduction	1
1.1	Background.....	1
1.2	Research questions.....	2
1.3	Thesis structure	4
1.4	References.....	5
2	Research trends in wildfire management studies in mediterranean-climate regions: An overview	7
2.1	Background.....	7
2.2	Materials and Methods.....	9
2.2.1	Geographic and ecosystem scope	10
2.2.2	Literature search.....	10
2.2.3	Selection criteria	11
2.2.4	Data extraction	11
2.3	Results and Discussion	13
2.3.1	Year of publication and place of study	14
2.3.2	Type of publication and journals	15
2.3.3	Web of Science research area and Scopus research field	16
2.3.4	Wildfire phase and central research topic	18
2.3.5	Main objective of the studies	20
2.3.6	Research methods	22
2.3.7	Main conclusions or contributions.....	23
2.3.8	Geographical, multidisciplinary, and timeframe trends.....	25
2.4	Conclusions.....	26
2.5	References.....	28
3	Wildfire environmental impacts: A comparison of the scientific findings, governmental concerns and experts' perceptions in Portugal	36
3.1	Introduction.....	36
3.2	Material and methods.....	38
3.2.1	Geographic scope.....	38
3.2.2	Literature search.....	39
3.2.3	Selection criteria	40

3.2.4	Data extraction	40
3.2.5	Document analysis	41
3.2.6	Survey	41
3.3	Results.....	42
3.3.1	Systematic review of the literature.....	42
3.3.2	Year of publication and place of study	43
3.3.3	Research methods and timeframe of the studies	45
3.3.4	Main ecosystem services impacted	46
3.3.5	Content analysis of ICNF reports.....	47
3.3.6	Expert perceptions on wildfire impacts	50
3.3.7	Comparison of the environmental impacts described in the literature, the reports, and survey	53
3.4	Conclusions.....	56
3.5	References.....	57
4	Carbon policy as a means to address climate change, and prevent wildfires and biodiversity loss in Portugal	63
4.1	Introduction.....	63
4.2	Methods	66
4.2.1	Approach.....	66
4.2.2	Order of Magnitude Analysis.....	68
4.2.3	Emission Factors	69
4.2.4	Emissions per Forest Area	70
4.2.5	Carbon Value	70
4.2.6	Carbon Savings by Avoiding Fires	71
4.2.7	Carbon Savings by Forest Management	72
4.2.8	Prescribed Burning Savings	72
4.2.9	Uncertainties	73
4.3	Results and Discussion	74
4.3.1	Magnitude of Revenues and Investments	74
4.3.2	Emission factors	75
4.3.3	Monetary value of the carbon sequestration service	77
4.3.4	Prescribed burning monetary savings	79
4.4	Conclusions.....	80
4.5	References.....	82

5	Conclusions	85
5.1	Empirical Findings.....	86
5.2	Theoretical Contributions	87
5.3	Policy Implications	88
5.4	Limitations and Future Work.....	89
	Appendix A	91
	Appendix B.....	113

List of Figures

Figure 1-1 - Research questions, methods, and main findings of each step of the study.	3
Figure 2-1 - Proportional global distribution of the land area of the five mediterranean-type ecosystems. Source: Adapted from [5].	8
Figure 2-2 - The five mediterranean-climate regions (MCR) are distributed on the western sides of continents between 30° and 40° latitude. Source: Keeley (2012).	10
Figure 2-3 - Structure of the content analysis.	12
Figure 2-4 - The methodological approach employed in the systematic mapping study, following an adapted version of the PRISMA guidelines [11].	13
Figure 2-5 - Distribution of studies analyzed per publication year (n=201).	14
Figure 2-6 - Distribution of publications analyzed according to the mediterranean-climate region (MCR) of focus (n=201).	14
Figure 2-7 - Distribution of studies within the individual Mediterranean Basin countries with more publications (n=117). Other individual or combined Mediterranean Basin countries account for 40 studies.	15
Figure 2-8 - Distribution of the types of publications retrieved (n=201).	16
Figure 2-9 - Overlap of the studies retrieved in each database (n=201).	16
Figure 2-10 - Distribution of studies following the wildfire phase they address: “Pre-fire,” “Emergency Response,” “Post-fire,” and combinations (n=201).	18
Figure 2-11 - Distribution of the central research topics of the analyzed studies.	19
Figure 2-12 - Distribution of the main objective of the studies.	20
Figure 2-13 - Distribution of the research methods employed by the analyzed studies.	22
Figure 2-14 - Distribution of the main conclusions of the studies (n=153).	24
Figure 2-15 – Summary of the main findings of the systematic mapping process.	27
Figure 3-1 - NUT II regions in Continental Portugal.	39
Figure 3-2 - Structure of the content analysis.	40
Figure 3-3 - The methodological approach used in the systematic mapping study, following an adapted version of the PRISMA guidelines [13].	43
Figure 3-4 - Distribution of studies analyzed per year of publication (n=50).	44
Figure 3-5 - Distribution of publications analyzed according to the NUTS II region the studies were conducted (n=50).	44

Figure 3-6 - Distribution of the research methods employed by the analyzed studies. Some studies used more than one research method.....	45
Figure 3-7 - Time after the fire that the studies were conducted (n=50).....	46
Figure 3-8 - Categories of ecosystem services impacted by wildfire most studied. Some studies addressed more than one ecosystem service impacted.....	46
Figure 3-9 - Ecosystem services impacted by wildfire most studied. Some studies addressed more than one ecosystem service impacted.....	47
Figure 3-10 - Number of reports available by year, according to the region of the country.	48
Figure 3-11 - Ecosystem services impacted according to the reports. Most reports identified more than one impact.	49
Figure 3-12 - Characterization of the 12 respondents. a) Institution of affiliation. b) Position occupied in the institution. c) Years working in the institution. d) Years working in the area.....	50
Figure 3-13 - Answers to the third and fourth questions of the survey. A) Refers to services with policies currently in place. B) Refers to services still lacking policies in the perception of the respondents.	52
Figure 4-1 - Framework of policies related to climate change, wildfires, and biodiversity in Portugal.	65
Figure 4-2 - Analysis framework employed. The white boxes represent data input, the black boxes the results of the calculations, and in grey boxes are the legislation or economic metrics used to compare and discuss the results.	67
Figure 4-3 - Structure of the order of magnitude analysis.....	69
Figure 4-4 - Order of magnitude analysis. The revenue from the Addition Tax in contrast with the costs of RCM N. 59/2017 and RCM N. 121/2019.	74
Figure 4-5 - The annual average CO ₂ equivalents emission factors from 1990 to 2018. The dashed line symbolizes the mean value of the annual average emission factor (20 Mg/ha). Developed based on data from PEA (2020).	76
Figure 4-6 - Monetary value of CO ₂ equivalents stored per hectare in the Portuguese forests.	77
Figure 4-7 - Monetary value of CO ₂ equivalents stored per hectare in the Portuguese forests, considering the effect of forest management (€/ha).	78

Figure 4-8 - Annual monetary savings associated with prescribed burning interventions,
according to the Addition Tax and the scenarios proposed by Vilén and Fernandes (2011).
..... 79

Figure 5-1 - Summary of the structure and findings of this thesis. 85

List of Tables

Table 2-1 - Number of papers analyzed in the six most frequent journals (n=201).....	16
Table 2-2 - Number of studies according to the number of areas (WoS) and Fields (Scopus).....	17
Table 3-1 - Level of impact for each ecosystem service reported by the respondents for the short and long (> 3 years after the fire) terms.	51
Table 3-2 - Ecosystem services impacted according to the scientific literature and ICNF's reports, by the region of the country.....	53
Table 3-3 - Ecosystem services not covered by the scientific literature and ICNF's reports, according to the region of the country.....	54
Table 4-1 - Variation of the Addition Tax on Carbon Emissions.	71
Table 4-2 - Scenarios description and calculated overall emission reductions in Portugal. Adapted from: Vilén and Fernandes (2011).	73
Table 4-3 - Emission factors for Portugal estimated in other studies.....	76

Glossary

Ecosystem services	The benefits human populations derive, directly or indirectly, from ecosystem functions, be it in the form of goods (such as food) or services (such as climate regulation). ¹
Forest fire	Any wildfire or prescribed fire that is burning in forested areas. The main types of forest fire are: ground fire, surface fire, and crown fire. ²
Payment for ecosystem services	Policy instrument designed to compensate people living in or near protected areas that provide the services for their losses. ³
Wildfire	An unplanned or unwanted natural or human-caused fire. ²
Wildfire management	The activities concerned with the protection of people, property, and forest areas from wildfire, conducted in a manner that considers environmental, social, and economic criteria. It encompasses both a land management philosophy and a land management activity, involving the strategic integration of such factors as knowledge of fire regimes, probable fire effects, values -at-risk, level of forest protection required, and cost of fire-related activities. Successful fire management depends on effective fire prevention, detection, and suppression, having an adequate fire suppression capability, and consideration of fire ecology relationships. ²
Wildland fire	Any non-structure fire that occurs in vegetation or natural fuels, including wildfires and prescribed fires. ⁴

¹ Adapted from: R. Costanza et al., “The value of the world’s ecosystem services and natural capital. LK - <https://royalroads.on.worldcat.org/oclc/4592801201>,” *Nat. TA - TT* -, vol. 387, no. 6630, pp. 253–260, 1997.

² Adapted from: C. I. F. C. CIFFC, “Canadian Wildland Fire Management Glossary,” *Canadian Interagency Forest Fire Centre: Winnipeg, MB, Canada*, 2017. [Online]. Available: https://www.cifc.ca/sites/default/files/2019-03/CIFFC_Canadian_Wildland_Fire_Mgmt_Glossary_2017_10_24.pdf.

³ Adapted from: B. Fisher and M. Christie, *The Economics of Ecosystem and Biodiversity: Ecological and Economic Foundations*., March. 2010.

⁴ NWCG, “NWCG Glossary of Wildland Fire, PMS 205,” 2021. [Online]. Available: <https://www.nwcg.gov/glossary/a-z>. [Accessed: 27-Dec-2021].

1 Introduction

This section presents the background and context in which this thesis was developed. In addition, the main research questions and a brief overview of this document's structure are also presented.

1.1 Background

Climate change is considered one of the greatest challenges of our time [1]–[4], having many consequences in various aspects of society and the natural environment. As is acknowledged by the European Commission, the climate crisis and the biodiversity crisis are linked. Climate change accelerates the degradation of the natural environment through more extreme meteorological events, while the unsustainable use and loss of nature are drivers of climate change [5].

In mediterranean-climate regions, such as the Mediterranean Basin, this is especially felt in the form of wildfires. Despite being a natural element of the mediterranean ecology, and perhaps one of the most important evolutionary forces [6], fire incidence has been increasing, and it is anticipated that it will become more prevalent in the future due to climate change [7]. These contemporary fire regimes are causing extensive environmental, social, and economic impacts due to the destruction of infrastructure, degradation of ecosystem services, loss of life, and smoke-related health effects [8].

Wildfires alter carbon sequestration by terrestrial ecosystems, and their emissions directly affect carbon cycles by increasing the atmospheric carbon dioxide (CO₂) [9], [10]. Given the extent of these impacts, forest and fire must be effectively managed [11]. It has been argued that wildfire management policies in mediterranean-climate regions need to change their focus to minimize the various social, economic, and environmental impacts of these events [12].

Forest fires are more common in the Mediterranean than in other regions in Europe [9], and Portugal, which has had its biodiversity impacted by wildfires [13], is regarded as an interesting case study for forest-management interventions [14]. In this sense, it can

be considered a characteristic representative of the Mediterranean region in terms of fire management practices.

Given this context, this thesis first focuses on understanding the current state of wildfire management in mediterranean-climate regions, especially in Portugal. This is done through a systematic mapping process that indicated a lack of studies using multidisciplinary methods to address the various fire impacts to the forests' ecosystem services.

Having identified these main knowledge gaps, the following two sections of this thesis aimed to address them, using Portugal as a case study, as the insights gathered for the country are likely valid and useful for nations in other mediterranean-climate regions. Aiming to address the multidisciplinary issue, in the second stage of this thesis, a triangulation approach was used to identify the main fire impacts and the policies to tackle them. In this stage, it became evident that not all ecosystem services impacted by fires were addressed or economically accounted for by the governmental agencies, especially in terms of climate regulation.

Considering that there is evidence linking climate change to the increasing occurrence of wildfires and that the wildfires impact the climate regulation service and biodiversity as a whole, these relationships were further studied through the policies currently in place in Portugal.

In this setting, this thesis's third and final stage consisted of an economic analysis of Portuguese policies that address climate change, biodiversity conservation, and fire prevention. Next, the research steps taken and the questions asked are explained in further detail.

1.2 Research questions

This study was conducted sequentially, as the answers and understanding of a previous step served as the foundation for the next. Figure 1-1 illustrates the questions asked in each stage of the research process, indicates the research methods employed, and

briefly summarizes the main findings that served as the basis for the following research questions.

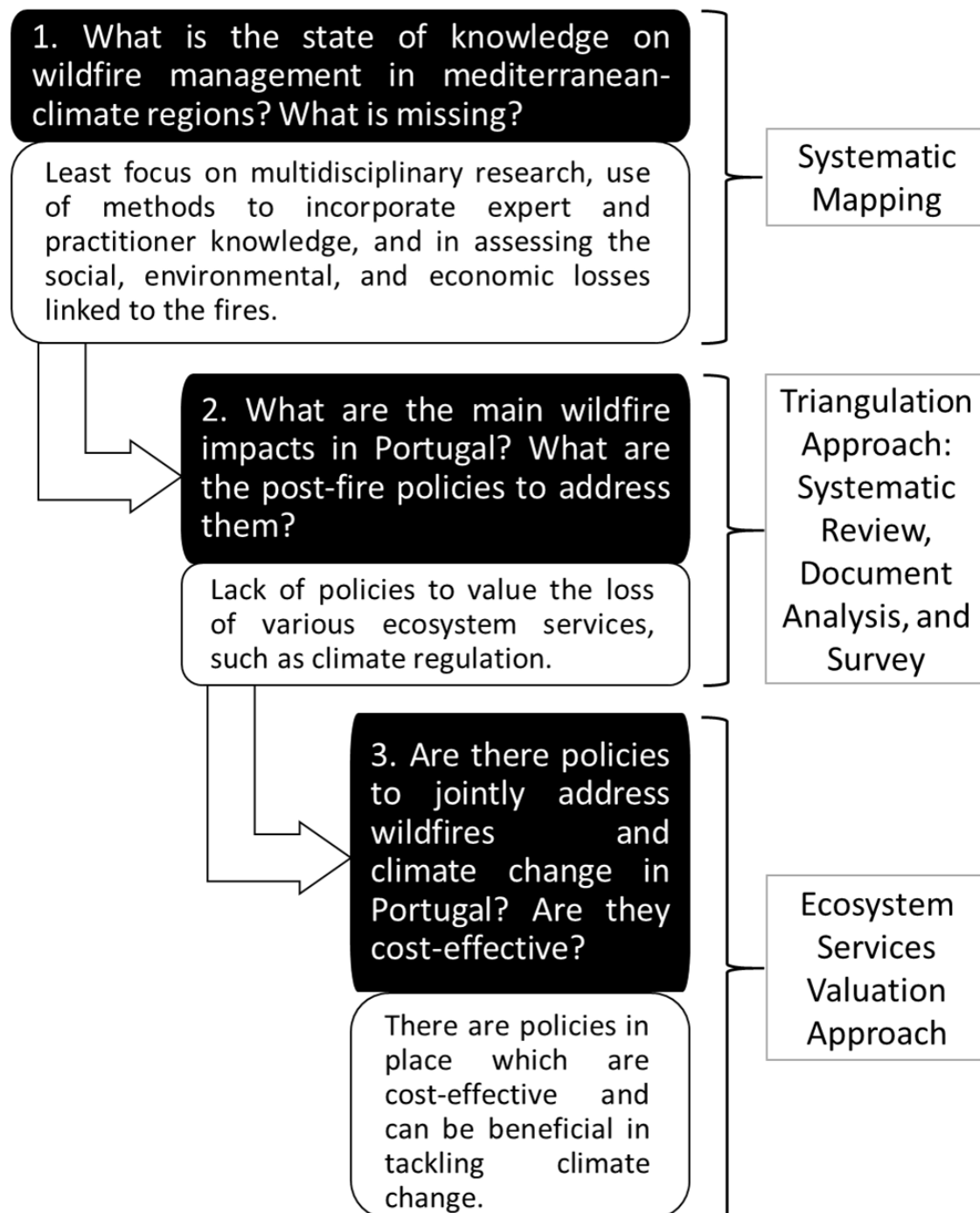


Figure 1-1 - Research questions, methods, and main findings of each step of the study.

To gather and catalog a robust body of evidence to describe the state of knowledge for wildfire management practices in mediterranean-climate regions, the first set of questions asked were: *What is the state of knowledge on wildfire management in*

mediterranean-climate regions? What is missing? Chapter 2 addresses these questions through a systematic mapping process. The main takeaways of this step were that not many studies focused on multidisciplinary research, employed methods to incorporate expert and practitioner knowledge, or aimed to assess the social, environmental, and economic losses linked to wildfires.

These findings motivated the second set of research questions: *What are the main wildfire impacts in Portugal? What are the post-fire policies to address them?* Chapter 3 shows how this question was addressed. In this setting, a triangulation strategy consisting of a systematic review, document analysis, and survey was the chosen approach. The central lessons learned in this stage were that the policies currently in place do not address the value of all ecosystem services lost to fire, especially climate regulation.

Finally, using the previous findings as the rationale, the third and last set of questions: *Are there policies to address wildfires and climate change in Portugal? Are they cost-effective?* These questions are addressed in Chapter 4, and an ecosystem services valuation approach was employed in this stage of the research.

The following subsection briefly explains the structure of the present work.

1.3 Thesis structure

This thesis is structured in five chapters. Chapter 1 (Introduction) introduces the knowledge context in which this study was developed and the structure of this thesis. Chapter 2 (Research trends in wildfire management studies in mediterranean-climate regions: An overview) addresses the first set of research questions asked, how the research was conducted, along with its findings and conclusions. Chapter 3 (Wildfire environmental impacts: A comparison of the scientific findings, governmental concerns and experts' perceptions in Portugal) addresses the second set of research questions, presents the methods employed and the findings and conclusions of this stage of the study. Next, Chapter 4 (Carbon policy as a means to address climate change, and prevent wildfires and biodiversity loss in Portugal) addresses the third set of research questions, shows the methods used, and describes the findings and conclusions of this step of the

study. Chapters 2 to 4 all have an “article” structure, i.e., these sections have their individual Introduction, Materials and Methods, Results and Discussion, Conclusion, and References subsections. Finally, Chapter 5 (Conclusions) presents the final considerations of this thesis, including the empirical findings, theoretical contributions, policy implications, and limitations and suggestions for future work.

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2 Research trends in wildfire management studies in mediterranean-climate regions: An overview

This chapter is based on the following work:

- R. Pacheco and J. Claro, “Wildfire management in mediterranean climates: A preliminary systematic review of the state of the art,” in *Book of Abstracts of the Symposium on Environmental Engineering. 3rd Doctoral Congress in Engineering.*, 2019, pp. 59–60.
- R. M. Pacheco and J. Claro, “A Systematic Map of the Research Trends in Wildfire Management in Mediterranean-Climate Regions,” in *XIV. International Conference on Forest Fire Disaster Management Forest Fire Disaster Management*, 2020, vol. 14, no. 11, pp. 325–334.

2.1 Background

Wildfires are an increasing concern worldwide, especially over the last decades [1], [2]. These contemporary fire regimes are causing substantial environmental, social, and economic disruptions due to the destruction of infrastructure, degradation of ecosystem services, loss of life, and smoke-related health effects [3]. Given the extent of these impacts, forest and fire must be effectively managed [2]. This is especially relevant in mediterranean-climate regions - MCR, in which fire is not only a natural component of the environment but also perhaps one of the most relevant evolutionary forces [4].

MCRs exist in all five continents of the world [5], and although they only appear in about 2% of the world’s total land area [6], these climatic regions are significant centers of human population growth [7]. The largest MCR is the Mediterranean Basin, corresponding to 73% of the total land area, followed by California and Southwestern Australia (10% each), Central Chile (4%), and the Cape region (3%) [5]. Figure 2-1 shows the proportional global distribution of the land area of the five mediterranean-type ecosystems.

The large presence of woody biomass and the dense cover of mediterranean-climate shrublands cause them to be very flammable, particularly under dry summer conditions with low humidity. Consequently, fire is a major disturbance in all mediterranean-type ecosystems, as its fire-adapted vegetation indicates [5]. Recent devastating fires in the Mediterranean Basin, Israel, California, South Africa, southern Australia [3], and Chile [7] suggest that this disturbance is intensifying.



Figure 2-1 - Proportional global distribution of the land area of the five mediterranean-type ecosystems.
Source: Adapted from [5].

Currently, human activities are the cause of most wildfire ignitions worldwide. More than 90% of forest fires are caused by people in European Mediterranean countries [8]. Consequently, understanding the diversity of natural, but especially anthropogenic, fire regimes is crucial to comprehend carbon cycles and to identify strategies to manage fire, aiming at decreasing emissions and increasing carbon storage [3], as well as reducing their social and economic impacts. Such an integrated approach, considering all social, economic, and environmental dimensions, is necessary to allow humanity to coexist sustainably with our inherently flammable planet [3].

Given that all MCRs share the same unusual climatic regime, mediterranean-type ecosystems have for long provided classic cases for comparative ecological function studies [5]. In this sense, considering that these regions have several similar structural features, it may be useful to examine trends in wildfire management research related to any of them, as the resulting knowledge might apply to all. The recent fire events in these regions have shown that, while fire management agencies on all five continents can lessen fire risks in these environments, they cannot entirely prevent fires from proliferating, including spreading to urban settings [3]. Taking into account that large-scale wildfires are becoming an increasing concern [9], and that, despite considerable government investment, consensus on fire and ecosystem management is still lacking [1], it is important to map the research trends on the topic and understand what has been focused and what is still missing.

Considering that the main goal of a systematic map is to gather and catalog a body of evidence to describe the state of knowledge for a particular topic or question [10], it is a suitable approach to be used for this purpose. Systematic mapping does not aim at answering a specific question as does a systematic review. Instead, it collates, describes, and catalogs available evidence, following the same rigorous, objective, and transparent processes, covering the breadth of science often needed for policy-based questions, as well as identifying knowledge gaps and knowledge clusters, to recommend future lines for systematic reviews and subjects for further empirical studies [10].

Accordingly, the objective of this study is to describe the research trends in wildfire management practices in mediterranean-climate regions through a systematic mapping process. The focus on management intends to synthesize and leverage the relevance and applicability of academic studies for policymakers and land managers who deal with wildfire-related issues in any of its phases (pre-fire, emergency response, and post-fire). The paper also aims at describing knowledge gaps for future academic research.

First, a global overview is provided by describing the wildfire management studies in terms of: year of publication; place of study; type of publication; name of publication; Web of Science research area; Scopus research field; wildfire phase; central research topic; objectives of the study; research methods; and main conclusions or contributions. Next, considering that the management of forests and wildfires is a concern in every continent, that it is multidisciplinary in nature, and that it involves different timeframes, a discussion is centered around the following questions that are relevant for the scientific community as well as for managers: “Have MCRs been uniformly studied?”; “Has wildfire management research been evenly focusing on the social, economic and environmental dimensions of its impacts?” and “Are all fire phases being equally addressed by the literature?”.

2.2 Materials and Methods

The methodological procedures are based on the work of James et al. [10] for systematic mapping in environmental sciences, on the PRISMA (Preferred Reporting Items for Systematic Reviews) guidelines for systematic reviews [11], and other studies with similar scopes [12], [13]. In the following sections, the scope and specifics of this study are described.

2.2.1 Geographic and ecosystem scope

Mediterranean-climate regions are present in all five continents; more specifically, they are found in California, Chile, South Africa, Australia, and the Mediterranean Basin [6]. The global distribution of this climatic type displays remarkably consistent patterns, showing a direct association to the general circulation of the world's atmosphere and its seasonal displacements. Areas of mediterranean-climate are situated between latitudes 32° and 40° north and south of the equator. Equatorward, the climate is likely to be desertic, and poleward precipitation values tend to increase, and rainfall is more dispersed throughout the year [4]. Figure 2-2 shows the location of all five mediterranean-type ecosystems of the planet.

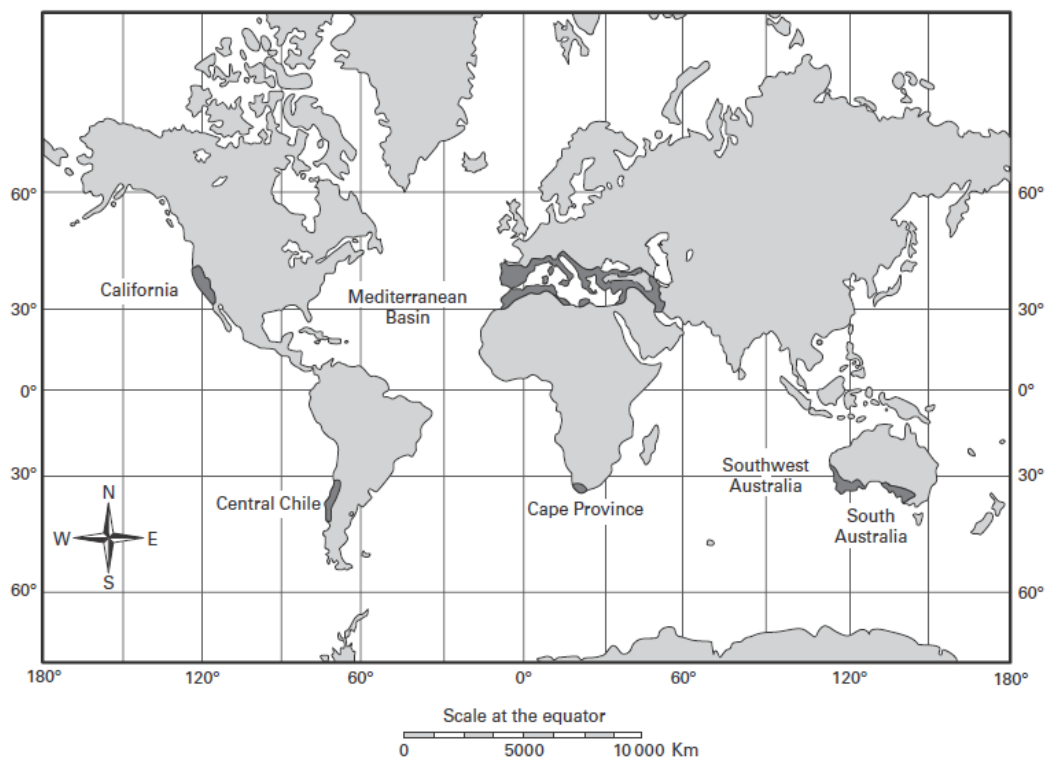


Figure 2-2 - The five mediterranean-climate regions (MCR) are distributed on the western sides of continents between 30° and 40° latitude. Source: Keeley (2012).

These regions have a tendency to exhibit mild, wet winters and warm, dry summers. This climatic regime usually has 90% or more of annual precipitation falling in the six cool season months and frequent periods of sustained droughts during the summer, causing the vegetation to be very flammable, that is, fire-prone [5].

2.2.2 Literature search

The search was centered on peer-reviewed studies that explicitly focused on issues related to wildfire management in mediterranean-climate regions. With that aim, we searched Elsevier's Scopus (*title*, *abstract*, and *keyword* fields) and Thomson Reuter's Web of Science (*title* and *topic* fields) online databases, as done in other systematic review studies [13], [15]. The searches were restricted to studies in English and used the following search string in both databases: **fire AND ("mediterranean-climate" OR "mediterranean environ*" OR "mediterranean region" OR "mediterranean eco*" OR "mediterranean forest") AND (manag* OR polic*)*. We used the asterisk (*) in some of the search terms to increase the number of retrieved studies. For example, in the case of **fire*, studies containing both "fire" and "wildfire" in one of the search fields are retrieved.

2.2.3 Selection criteria

Once the searches were done, the title, abstract, and keywords of the studies were reviewed to verify if they were within the scope of this study. Then, the following inclusion criteria were applied to select the studies to be further analyzed: *Partially or totally about a region of mediterranean-climate* (studies that reported being conducted in a mediterranean-climate region were accepted) and *Addresses situations directly linked to any stage of wildfire management*. The exclusion criteria were the following: *Not about mediterranean-climate regions*; *Not focused on wildfires*; *Not focused on the management of situations linked to wildfires*; and *Only provides information that could help in the development of management practices or public policies about wildfires* (but management was not the focus).

2.2.4 Data extraction

Ensuing the screening phase, the full texts of the selected studies were downloaded and reviewed. Then, information was extracted from each paper according to the following analysis topics: *Year of publication*; *Place of study*; *Type of publication*; *Name of publication*; *Web of Science research area*; *Scopus research field*; *Wildfire phase*; *Central research topic*; *Objectives of the study*; *Research methods*; and *Main conclusions or contributions*. Figure 2-3 shows the type of information collected from each study, according to the analysis topic.

Year of publication	• Years
Place of study	• Mediterranean-climate regions or countries
Type of publication	• Journal, conference, book or news
Name of publication	• Name of the scientific outlet
Web of Science Research Area	• Research area, as indexed by Web of Science
Scopus Research Field	• Research Field, as indexed by Scopus
Wildfire phase	• Pre-fire, emergency response, post-fire, or combinations
Central research topic	• 16 categories
Main objective of the studies	• 18 categories
Research methods	• 12 categories
Main conclusions or contributions	• 14 categories

Figure 2-3 - Structure of the content analysis.

For the analysis of the last four topics, as characteristic of systematic mapping studies [10], coding systems were employed since those forms of information are not standardized. To analyze the “main research topic” each study addressed, a coding system based on the research topics proposed by The International Association of Wildland Fire [16] was used. Other categories were also aggregated to better characterize the topics of the studies (see link in Appendix A). Figure 2-11 shows the codes used.

Regarding the “objectives of the studies,” the coding system employed is parallel to the “central research topic,” but wording alterations were made, and more categories were added to better reflect the goals of the publications, as displayed in Figure 2-12.

The coding system applied to analyze the “research methods” used in every study is based on the categories employed in the systematic review performed by Krajter Ostoić et al. [13], who conducted a study with a similar scope. Still, the category “Field observations and assessments” used in that study was suppressed since, in the present work, all field studies conveyed some form of measurement or sampling, and either the “Field measurements” or the “Field sampling and/or laboratory analysis” categories better applied. Figure 2-13 displays the twelve categories employed to classify the studies.

The final aspect analyzed in each study was its “main conclusion or contribution,” as reported by its authors. Once more, the coding system employed in this analysis is similar to the “Objective of the study,” as it is expected that the conclusion is aligned with the focus of the research. Figure 2-14 describes the categories used in this analysis.

2.3 Results and Discussion

The search on both databases was conducted on February 19th, 2019. Altogether, the literature search yielded 1042 studies, of which 613 were found on Scopus and 429 on Web of Science. Once the duplicates were removed, a total of 743 studies remained to be screened by reading the abstracts and applying the previously established inclusion and exclusion criteria. In this stage, 535 studies were excluded. Most of them either did not focus on wildfires (i.e., wildfires were a secondary issue on the study) or only supplied information that could assist in the advancement of wildfire management practices or public policies, i.e., they were mostly focused on describing ecological processes or physical phenomena instead of how to manage them. Ultimately, 208 studies were left for information extraction. Of those, 202 were found, and one was excluded after reading the full text as it was not focused on a mediterranean-climate region. Most of the studies that could not be retrieved were either from conferences or not included in the institutional subscriptions to which there was access. Figure 2-4 describes the process mentioned previously.

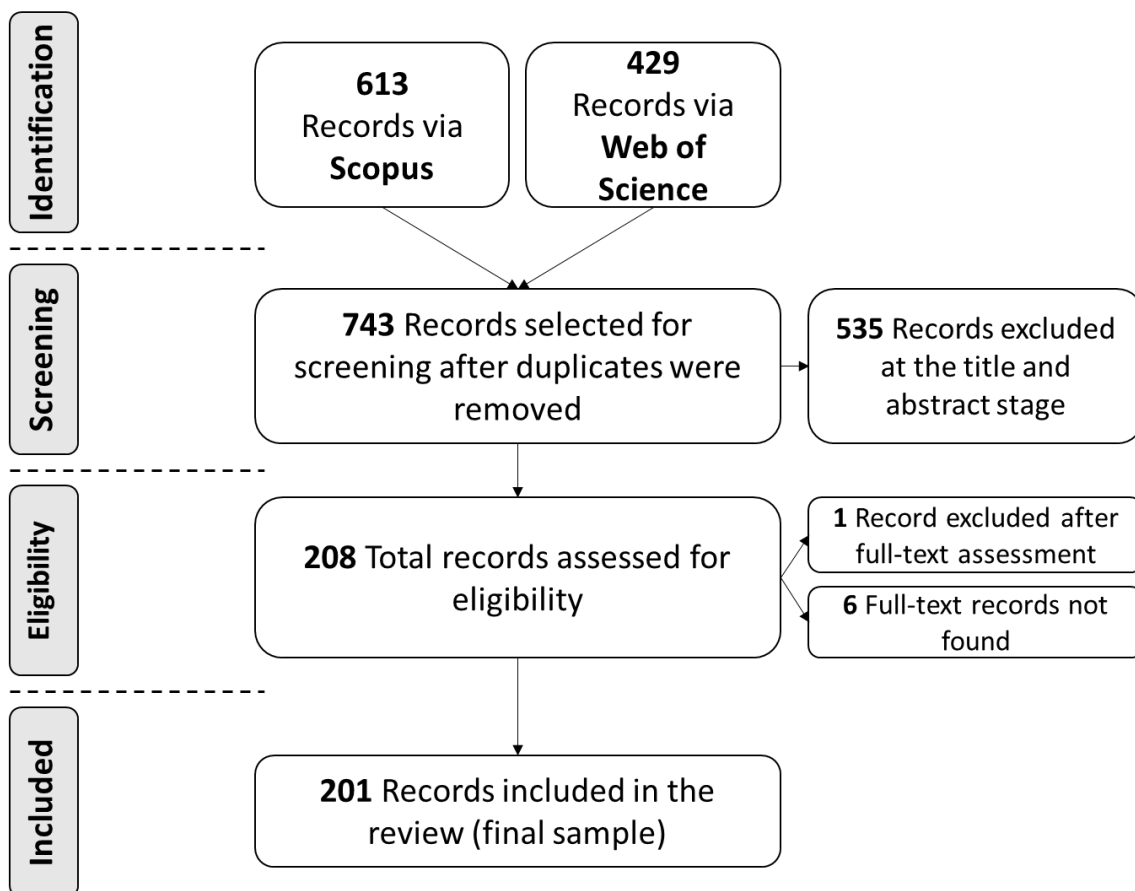


Figure 2-4 - The methodological approach employed in the systematic mapping study, following an adapted version of the PRISMA guidelines [11].

Next, the main results from the 201 studies reviewed for the systematic map are discussed, following each topic of analysis. It is worth mentioning that no systematic review or systematic mapping studies were found in the searches, which reinforces the novelty and relevance of this research effort. Studies that illustrate the findings are referenced along with the discussion. For more specifics on the studies, please refer to the link in Appendix A.

2.3.1 Year of publication and place of study

The distribution of the publication year of the studies spanned from 1996 till 2019 and displayed an increasing trend over time, as shown in Figure 2-5. However, it should be emphasized that the search on the databases was done in February of 2019, for this reason not all studies of that year are considered.

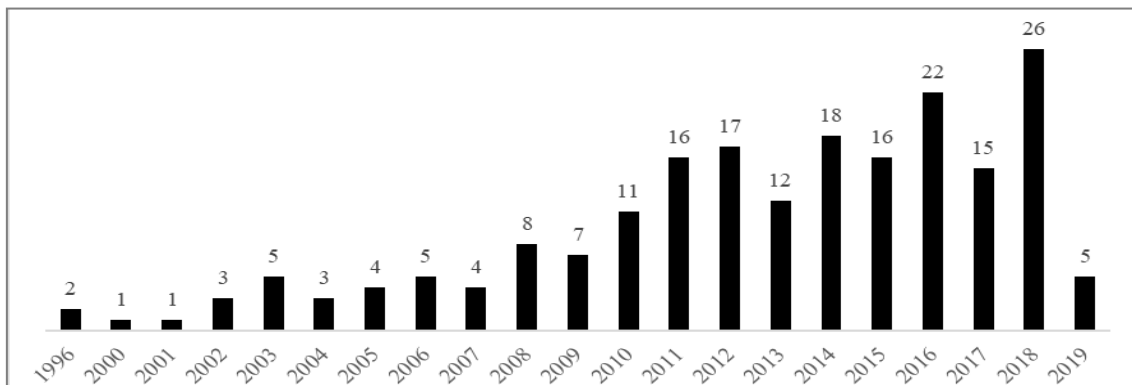


Figure 2-5 - Distribution of studies analyzed per publication year (n=201).

Regarding the places of study, their distribution according to the mediterranean-climate region of focus is illustrated in Figure 2-6.



Figure 2-6 - Distribution of publications analyzed according to the mediterranean-climate region (MCR) of focus (n=201).

Most of the studies (78%) were held in the Mediterranean Basin. This is to be anticipated as this region encompasses around 73% of the world's mediterranean-climate

area [5]. Analyzing the percentages of land area belonging to each MCR, it is perceptible that the number of studies per region is proportional to their size.

Most studies focus only on a specific place (as a natural park) in a particular country [17]–[21]. Even so, 15 studies (7%), such as those by Henderson et al. (2005) and Urbietta et al. (2015), compared experiences and outcomes in more than one MCR.

However, within the Mediterranean Basin, the number of studies is not distributed in correspondence to the size of the country of focus, as illustrated in Figure 2-7.

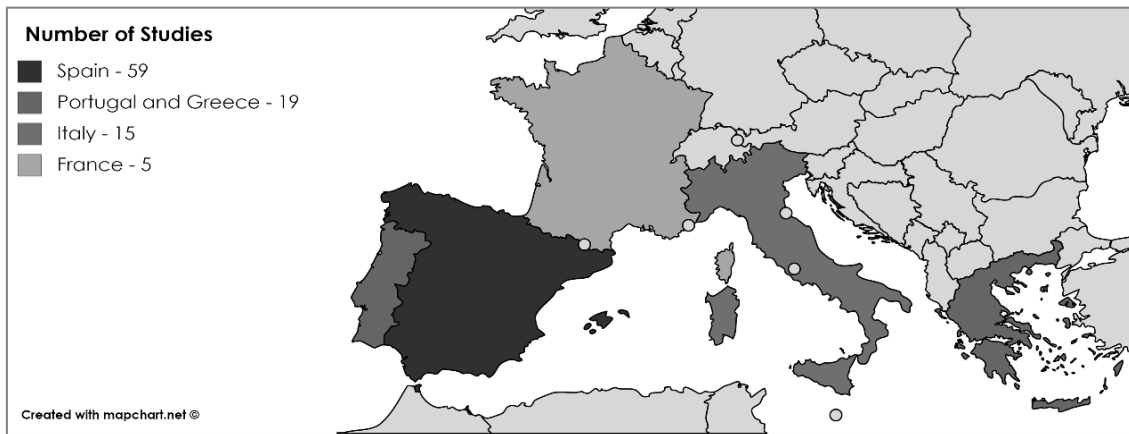


Figure 2-7 - Distribution of studies within the individual Mediterranean Basin countries with more publications (n=117). Other individual or combined Mediterranean Basin countries account for 40 studies.

Spain is the country with most studies, responsible for more than one-third of the publications within the Mediterranean Basin. This may be because Spain is one of the countries most impacted by wildfires in Europe, considering the number of fires and burnt area [24], which might also lead to more investments in this research field. Portugal and Greece individually account for 12% of the studies within the Mediterranean Basin, both countries having recently been through severe wildfire events. Next, Italy and France, respectively, account for 9% and 3% of the studies within the Mediterranean Basin. These five countries amount to nearly 75% of the studies done within the Mediterranean Basin and around 60% of the total number of studies analyzed. This suggests that research in the field of fire management is highly concentrated in few countries despite being a concern in five continents.

2.3.2 *Type of publication and journals*

As presented in Figure 2-8, most of the studies found in the searches were papers published in journals (92%), followed by conference proceedings (4%) and books or book chapters (4%), and only one was news of an official governmental institute [25].



Figure 2-8 - Distribution of the types of publications retrieved (n=201).

The 201 studies analyzed were published in a total of 100 different publication outlets. More than 30% of the papers analyzed were published in the six journals shown in Table 2-1.

Table 2-1 - Number of papers analyzed in the six most frequent journals (n=201).

Journal	Number of Studies
Forest Ecology and Management	19
Journal of Environmental Management	16
International Journal of Wildland Fire	15
Science of the Total Environment	7
European Journal of Forest Research	6
Environmental Management	5

From the 95 remaining outlets, 3 published four studies, 7 published three studies, 17 published two studies, and 66 (30%) had only 1 study published. This suggests that the research on the management of wildfires in mediterranean-climate regions tends to be specialized, and few journals are responsible for a considerable portion of the publications on the field.

2.3.3 Web of Science research area and Scopus research field

From the 201 studies analyzed, 179 (89%) were found on both databases, 21 (10%) only on Scopus and one only on Web of Science, as illustrated by Figure 2-9.

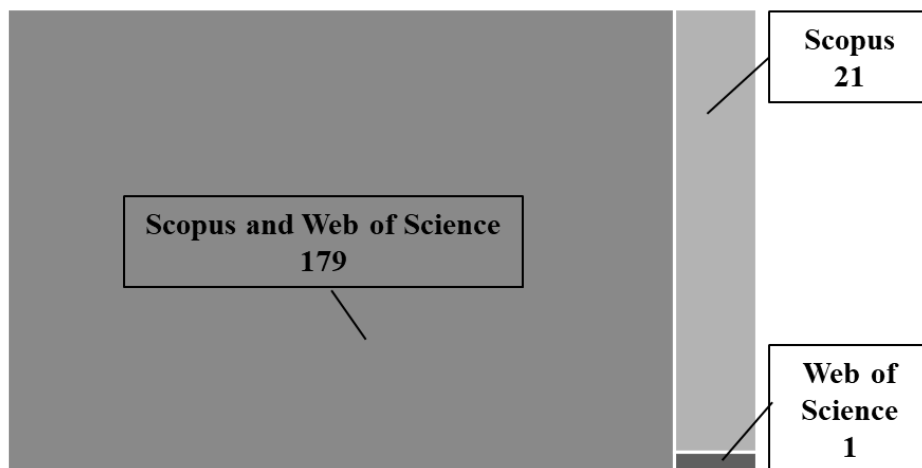


Figure 2-9 - Overlap of the studies retrieved in each database (n=201).

The fact that Scopus rendered more results is relevant to note since some systematic reviews and maps with an environmental scope only use Web of Science as the database [26], [27], and that may be reducing the total number of studies retrieved.

Most environmental studies are multidisciplinary by nature, so it is relevant to analyze how the scientific outlet is cataloged in each database. On Web of Science, the outlets were classified under 37 different areas, while in Scopus, they were classified under 19 fields. Table 2-2 shows how many studies were classified according to the number of areas (Web of Science) and fields (Scopus) in each database.

Table 2-2 - Number of studies according to the number of areas (WoS) and Fields (Scopus).

Number of areas (WoS) / fields (Scopus)	Number of Studies WoS	Number of Studies Scopus
1	108	86
2	35	88
3	31	17
4	6	8
5	0	1
Total	180	200

On Web of Science, most studies were classified under only one area (60% of the studies found on the database), being that both “Forestry” and “Environmental Sciences” accounted for more than 30% of the studies each, followed by “Ecology,” which accounted for more than 16% of the total. Even though these areas are considered multidisciplinary, the database did not index the outlets the studies were published in multiple areas, which could potentially help in their retrieval by researchers searching by specific areas of knowledge.

As for Scopus, almost the same number of studies were classified under one or two fields (43% and 44% of the studies found on the database, respectively). Of the studies classified under only one field, “Environmental Science” and “Agricultural and Biological Sciences” were the most common, respectively representing 24% and 10% of the studies retrieved in the database. As for the studies published in outlets indexed under two fields, the most common combination was exactly “Environmental Science” and “Agricultural and Biological Sciences,” representing almost 30% of the studies found on this database. Considering this, Scopus seems to be a database that is better adapted to deal with multidisciplinary studies.

It is also interesting to note that about 2% of the retrieved studies in both databases were published in outlets classified under the “Economics” area (WoS) or “Economics, Econometrics, and Finance” field (Scopus). Considering that “management” and “policy” were two of the keywords used, and usually social, environmental, and economic aspects

should be accounted for in these contexts [28], [29], more studies that addressed economic issues related to fire management were expected.

2.3.4 Wildfire phase and central research topic

Regarding the wildfire phases, the following classification was employed for the studies: “Pre-fire,” when they were centered on management aspects that happen prior to the wildfire occurrence, such as fire prevention measures and fuel management; “Emergency Response,” when the focus was on the actions to take place during the wildfire occurrence, such as the optimization of the use of fire-fighting resources; and “Post-fire,” when the study dealt with issues that followed the occurrence of the wildfires, such as the mapping of the burned area and salvage logging. Some studies addressed more than one fire phase, so all possible associations of the previous three categories were also considered. Figure 2-10 illustrates the distribution of studies corresponding to the fire phase they focus on.

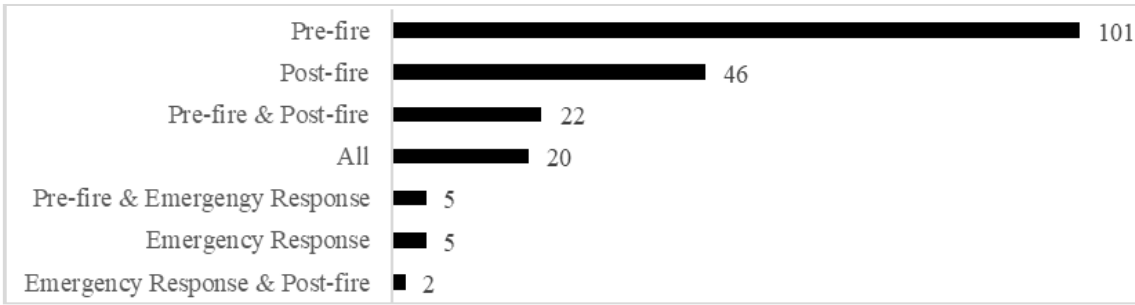


Figure 2-10 - Distribution of studies following the wildfire phase they address: “Pre-fire,” “Emergency Response,” “Post-fire,” and combinations (n=201).

More than 50% of the studies focused on Pre-fire concerns, while about 23% dealt with Post-fire issues. About 11% of the studies addressed situations connected to both Pre-fire and Post-fire aspects, mostly because they utilized past wildfire data to create predictive models of fire behavior or the most appropriate pre-fire interventions [30]–[32]. For instance, De Luis et al. [31] employed post-wildfire seedling germination data to try to determine if future fire prescriptions would be advisable from an ecological viewpoint.

About 10% of the studies tackled all wildfires phases, and it became evident that their objective was more of a social nature, trying to understand the origins of fires and their impacts on society [23], [33], [34]. For example, Henderson et al. [23] compared the social experiences of wildfires in Greece and the United States, exposing parallels in both places, such as the demise of traditional fire practices.

Around 6% of the studies addressed “Emergency Response” by itself or associated with other fire phases. Among the ones that focused exclusively on “Emergency Response,” most addressed operational aspects [35]–[37], such as the determination of response times for the deployment of terrestrial resources for wildfire fighting [36]. The rest of the studies were largely concerned with predicting wildfire behavior to support fire-fighting measures [38], [39], such as attempting to predict daily fire occurrence with readily available spatio-temporal data [38].

Regarding the “central research topic” of the studies, Figure 2-11 displays the seven most frequent categories observed from a total of 16 categories. It is worth noting that some studies had more than one central focus.

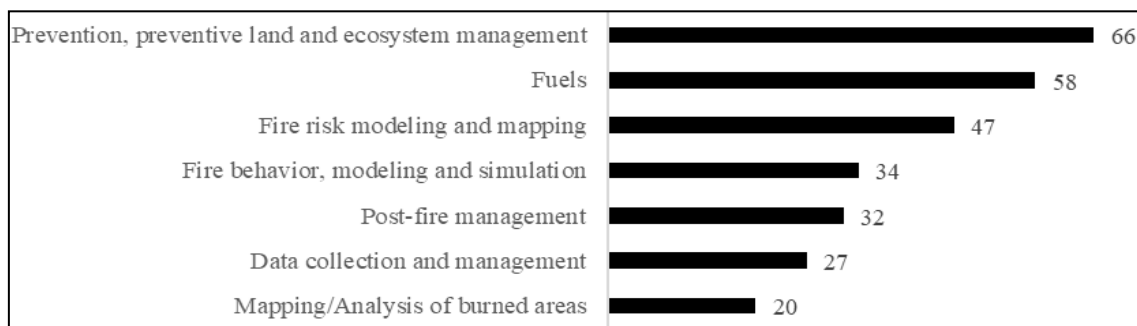


Figure 2-11 - Distribution of the central research topics of the analyzed studies. Other less frequent categories were: “Human factors and issues” (13); “Economic modeling” (12); “Firefighting and crisis management” (10); “Climate change” (9); “Megafires” (6); “Biodiversity” (1); “International cooperation” (1); “Lightning-ignited wildfires” (1); “Reburns” (1). Some studies had more than one central research topic.

Around 12% of the studies were classified as having three central research topics, 45% as having two central research topics, and 43% as having only one central research topic. No time trends were evident in terms of an increasing focus on a specific research topic (see graph in the link in Appendix A). Since over 50% of the publications addressed Pre-fire issues, it is consistent that the four most frequent central research topics regard that fire phase. About 33% of the studies had “Prevention, preventive land, and ecosystem management” as one of the central research topics, followed by 29% dealing with “Fuels,” 23% addressing “Fire risk modeling and mapping,” and 17% on “Fire behavior, modeling, and simulation.”

Publications that focused on “Post-fire” issues represented around 23% of the total, which is coherent with the fact that about 16% of the studies had “Post-fire management” as the research topic. Regarding the studies that analyzed “All” fire phases, most of them (60%) had at least one of the research topics related to “Data collection and management.”

Around 6% of the studies had “Economic modeling” as one of their central research topics despite only 2% of the studies being published in outlets classified in the “Economics” (WoS) or “Economics, Econometrics, and Finance” (Scopus) fields. Pondering that “management” and “policy” were two of the keywords used, and social, environmental, and economic aspects should be considered in these contexts [28], [29], more studies dealing with economic issues related to fire management were expected to be found, especially in outlets more deeply rooted in the economics field.

2.3.5 Main objective of the studies

Regarding the “main objective of the study,” a total of 18 categories were found and, similarly to what was noticed in the “Central research topic,” no trends of increase or decrease in time of studies having specific objectives were noticed (see graph in the link in Appendix A). Figure 2-12 displays the eight most frequent categories observed.

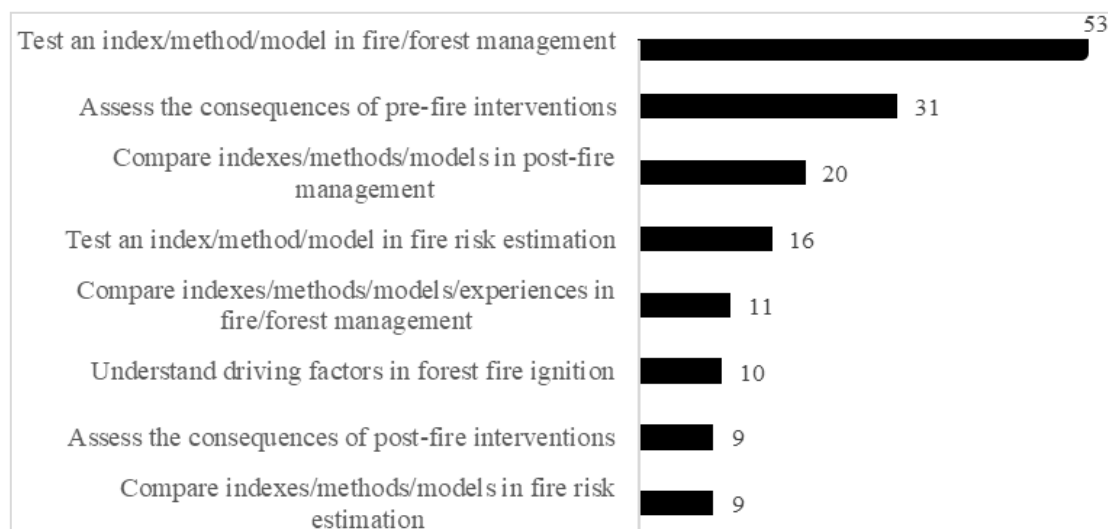


Figure 2-12 - Distribution of the main objective of the studies. Other less frequent categories were: “Economically compare ecosystem/fire management options” (6); “Publicize/Analyze the results of a research collaboration initiative/specialists group” (6); “Quantify a relevant management variable” (6); “Assess the consequences/potential use of a technology/software” (5); “Understand post-fire debris flow/erosion/runoff” (5); “Assess the impacts of climate change on forest management” (4); “Elicit personal preferences about fire prevention/Elicit specialists perception on fire management” (4); “Understand driving factors in megafires” (3); “Assess the consequences of fire interventions” (2); “Understand the impacts of reburns in future wildfires” (1).

Examining the results jointly, four types of research objectives can be highlighted in terms of the actions they entail. They aimed to: Test (34 %); Assess (25%); Compare (23%); and Understand (9%). Studies with these objectives addressed all fire phases. The ones that aimed to “Test” were designed to analyze either indexes, methods, or models for the management of fire or forests or to estimate fire risk [39]–[42]. The ones aiming to “Assess” mostly described the consequences or the impacts of environmental

interventions, climate change, and the use of technologies [43]–[45]. The studies that aimed to “Compare” mostly contrasted different management options or fire risk estimation methods, either in terms of their efficiency or economically [46]–[49]. Lastly, the studies that sought to “Understand” mostly focused on describing or modeling driving factors or physical phenomena to support management actions [50]–[53].

Individually, the three most frequent objective categories correspond to more than 51% of the studies. This indicates that, even though there is a reasonably broad spectrum of possible research objectives, most studies try to address similar research questions, even within different contexts. For instance, over 26% of the studies had “Test an index/method/model in fire/forest management” as the main objective. The studies in this category are extensive in scope, varying from cattle grazing and vegetation management for multiple land-uses [54], or the use of GIS-based decision support systems to optimize the route to forest fires [35], to the proposition of a framework for comprehensive wildfire management [55].

The second most frequent research objective, corresponding to more than 15% of the studies, is to “Assess the consequences of pre-fire interventions.” Considering that over 50% of the studies are centered on Pre-fire issues, it is coherent that many studies specifically address the consequences of interventions that occur prior to the wildfires. The scope of themes within this category is narrower, being that most address forest and fire management issues [17], [56]–[58] or fuel management [18], [59], [60]. It is noticeable that all mediterranean-climate regions have studies with this research objective, which might be indicative of its central importance in fire management.

To “Compare indexes/methods/models in post-fire management” was the third most frequent research objective, adding up to almost 10% of the studies. This is to be expected since more than 15% of the studies have “Post-fire management” as their central research topic. The studies with this objective did not vary much in scope, most addressing the consequences of post-fire interventions in soil erosion processes [46], [61], [62] or vegetation dynamics and salvage logging [63]–[65]. Studies with this research objective were only conducted in the Mediterranean Basin and California. Likewise, studies aiming to “Understand post-fire debris flow/erosion/runoff” were performed in these same regions [51], [66], [67]. These studies represent a bit over 2% of the total and differ from the previous category because instead of aiming to manage a post-fire situation, they focus on just trying to model it and propose guidelines to manage the identified issues. Regarding the objectives with fewer studies, they were mostly either

specific in scope (climate change effects, mega-fires, rekindles, among others) or focused on the “Emergency Response” fire phase, which was the least studied of all phases.

2.3.6 Research methods

Regarding the research methods, Figure 2-13 shows the nine most frequently observed categories, being that some studies employed more than one. In terms of methodological approach, most studies (about 84%) employed quantitative research methods, which are linked to rational and objective measurements of observable phenomena. Only 16% of the analyzed studies used at least one qualitative method, focusing on the assessment of subjective phenomena (e.g., ideas, opinions, patterns). It should be stressed that only 2% of the studies used both quantitative and qualitative methods. This may indicate a deficit in the field since, in the context of environmental management, there is a growing body of literature asking for integrated approaches in which the two research paradigms are seen as complementary [29].

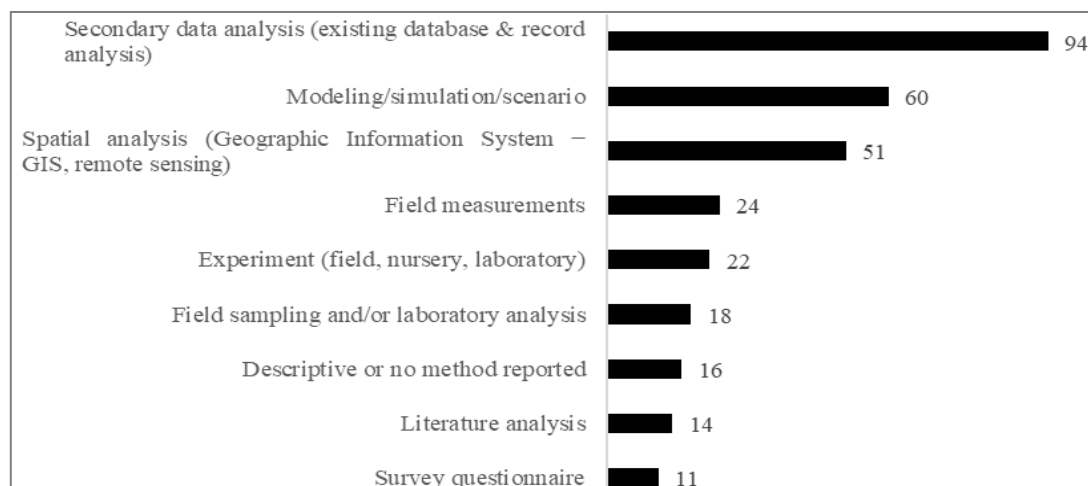


Figure 2-13 - Distribution of the research methods employed by the analyzed studies. Other less frequent categories were: “Focus groups/workshops” (4); “Interviews” (4); “Other” (1). Some studies used more than one research method.

Regarding the number of methods employed, 59% of the studies used two. The most frequent association was “Modeling/simulation/scenario” and “Secondary data analysis,” which accounted for 16% of the studies. Most of these studies (12% of the total) had as main objective to “Test an index/method/model in fire/forest management,” which shows an agreement between the objective of the research and the method employed, especially when considering that for modeling studies there is a need to have a sound database available. Employing these methods and with this objective, studies

from the North and South America mediterranean-climate regions [20], [68] were found, besides various countries from the Mediterranean Basin [30], [69].

The second most frequent combination of research methods was “Spatial analysis” and “Secondary data analysis,” which adds up to 12% of the studies. Once again, to “Test an index/method/model in fire/forest management” was the most frequent objective of the studies, representing 5% of the total. The main difference in this context is that most studies deal with spatial models, using satellite or terrain data to map or quantify relevant fire management variables [70]–[73]. Within this scope, studies from South America [70] and Australia [71] were found, but the majority is from the Mediterranean Basin.

Around 42% of the studies used a single method. In this single-method scenario, “Secondary data analysis” was the most used research method, corresponding to 10% of the studies. Studies that use this method were found on all the mediterranean-climate regions, and most of them address temporal fire trends [22], [74], [75]. Reasonably, secondary data (especially databases) are needed to perform this type of temporal study. The second most used single method was “Descriptive or no method reported,” accounting for 7% of the studies. This method was mostly used in books and more qualitative papers. Studies of all mediterranean-climate regions used this method [14], [33], [76].

Overall, only around 32% of the studies comprised some form of fieldwork [63], [64], [77]. Most of the work that was not included in this systematic mapping study was fieldwork since, even though it may bring valuable insights for fire or forest management practices, these were not their focus.

Finally, only seven studies employed either “Interviews” or “Focus groups/workshops,” which are methods most often used in social science research. Some of them aimed at integrating local actors into fire policy development [34], [78], others analyzed human factors linked to fire management [79], [80], or aimed at incorporating expert knowledge in the development of new fire policies [19], [64]. Considering that studies with interdisciplinary approaches, particularly those that embrace the inclusion of the “social” in the research, are valuable in tackling environmental management problems [29], there is an indication of a knowledge gap in the area and potentially relevant research opportunities.

2.3.7 Main conclusions or contributions

Regarding the studys' conclusions and contributions, Figure 2-14 displays the five most frequent categories. As anticipated considering the previous analysis, no trends were observed in time (see graph in the link in Appendix A).

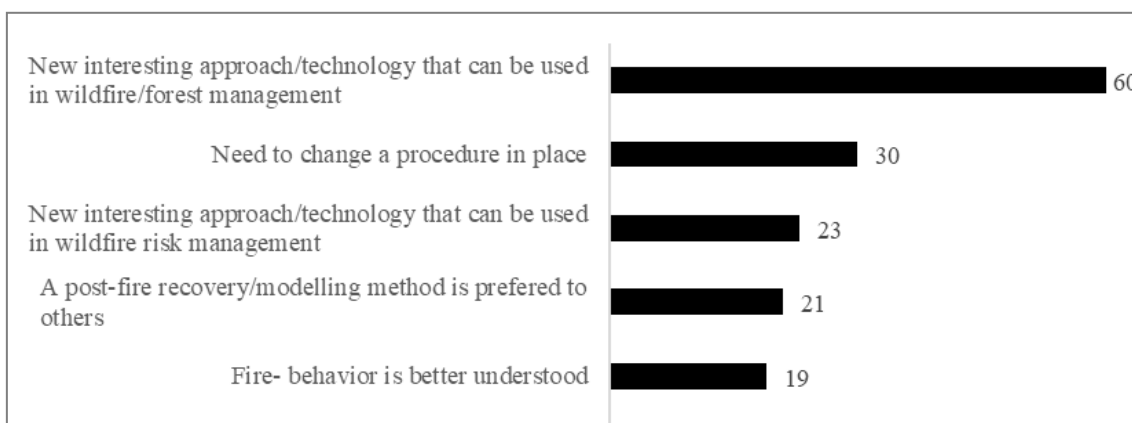


Figure 2-14 - Distribution of the main conclusions of the studies (n=153). Other less frequent categories were: “Further studies are needed” (10); “Social-economical aspects in fire management are better understood” (9); “A new concern that needs to be managed was found” (8); “An approach/technology/index is better than another in predicting wildfires” (6); “An approach/technology/index is better than another in mapping burned areas” (4); “A fuel reduction treatment is more adequate than the other” (3); “Megafire causes are better understood” (3); “Procedures in place are working” (3); “Fire-fighting strategies and characteristics are better understood” (2).

Roughly 30% of the studies contributed by offering a “New interesting approach/technology that can be used in wildfire/forest management” and more than 11% by proposing a “New interesting approach/technology that can be used in wildfire risk management.” In the first instance, over half of those studies had the objective to “Test an index/method/model in fire/forest management,” and more than 30% focused on “Pre-fire” issues. Studies from three mediterranean-climate regions were found within this context [19], [55], [81]. In the second instance, about half of the studies had as the goal to “Test an index/method/model in fire risk estimation,” and considering that “fire risk” is the topic, all of them were focused on “Pre-fire” or “Pre-fire & Post-fire” issues. Only studies from California and the Mediterranean Basin were found within this scope [82], [83]. Overall, this suggests that new and potentially useful knowledge, both in terms of procedures and technology, is being produced for forest, fire, or wildfire risk management, and perhaps the mediterranean regions that have not performed studies within this scope may also benefit from it.

Around 15% of the studies concluded that there was the “Need to change a procedure in place,” especially in terms of data collection and management measures as well as preventive practices. About one-third of these studies had the objective to “Compare indexes/methods/models/experiences in fire/forest management.” All but one

of the studies within this scope focused on “All” fire phases, and most were conducted in the Mediterranean Basin but included other regions [23], [84]. This suggests that perhaps newer practices and models can better assist in fire or forest management. In this same sense, only three studies concluded that “Procedures in place are working” [43], [79], [85], which supports the argument that more scientific knowledge for forest management is needed.

Finally, less than 1% of the studies contributed regarding developments in fire-fighting, which agrees with the fact that only 2% of the studies focused on the “Emergency Response” phase. This reinforces the observation that most of the research efforts in wildfire management are not directed at fire-fighting or suppression, unlike most public investment, which has tended to favor fire suppression over prevention [9], [86].

2.3.8 Geographical, multidisciplinary, and timeframe trends

In this section, the questions posed in the introduction on this study (“Have MCRs been uniformly studied?”; “Has wildfire management research been evenly focusing on the social, economic, and environmental dimensions of its impacts?” and “Are all fire phases being equally addressed by the literature?”) are now addressed based on the information gathered along the systematic mapping process.

Concerning the first question, the study shows that MCRs have not been uniformly studied. Almost two-thirds of the studies are conducted on the Mediterranean Basin and focused on five European countries. Only 7% of the studies involved more than one region. Even though the number of studies is proportional to the size of regions, there appear to be opportunities for greater research collaboration between them, especially considering that the number of wildfires has kept increasing [81–83] and the challenges are similar across regions.

Wildfire management requires knowledge from multiple disciplines. Nevertheless, the results showed that the publication outlets have tended to be indexed in a limited number of knowledge areas. Considering, once more, that wildfire occurrences are increasing, more multidisciplinary work capable of better addressing the complexity of the problem may be needed to tackle it effectively. In this sense, by analyzing the “central research topics,” it stands out that only 12% of the studies addressed “Economic modeling” or “Human factors and issues.” This suggests that the triple bottom line of the sustainability argument (social, environmental, and economic) is not being

homogeneously addressed by fire management research, which may negatively impact professional development and practitioners [22]. This finding is further corroborated by the Forest Service of the US Department of Agriculture, which has acknowledged that some fire impacts have not been researched from a social science perspective [84].

Additionally, the United States National Wildfire Coordinating Group has recognized that social issues have broadened the scope of the fire hazard problem, making fire management more extensive and complex. They also have highlighted the need for scientific research that includes sociological and economic factors [21]. Regarding the second question, the study results demonstrate that wildfire management research has not been focusing evenly on the social, economic, and environmental dimensions of its impacts.

In terms of the fire phase, most studies addressed “Pre-fire” issues, more specifically with central research topics related to preventive measures and fuel management. In this sense, this research trend seems to be aligned with European guidelines that are “shifting the focus from suppression to prevention and increasing the awareness and preparedness of populations at risk” [80]. Nevertheless, more studies are needed to understand the social and environmental components of the costs associated with fire-fighting and land recovery [8], especially since their costs tend to be higher than the ones associated with preventive measures [9]. As is clear from the above, regarding the third question, fire phases are not being equally addressed in the literature.

Finally, it stands out that wildfire management research in MCRs has been uneven in its focus, be it in terms of geography, dimensions of impact, or timeframes. There may be a need for more socio-economic methods and mixed research approaches to better reflect the entire wildfire phenomena in mediterranean-climate regions across all fire phases. This approach might be especially relevant since not all five regions had studies that employed various research methods, and combining qualitative and quantitative methods is considered necessary when trying to address the big picture of environmental management [22].

2.4 Conclusions

The systematic map presented here provides a rigorous account of the wildfire management studies conducted in every mediterranean-climate region. Figure 2-15 shows a summary of the main lessons learned during the systematic mapping process.

Most studies are...
From the last 10 years
Conducted in the Mediterranean Basin
Focused on pre-fire issues
Not focused on economic modeling or human factors and issues
Testing new approaches in fire or forest management
Not employing research methods that tackle social issues or address expert and practitioner's knowledge

Figure 2-15 – Summary of the main findings of the systematic mapping process.

The results showed that there is an increasing number of studies being carried out on the topic, but most of them are conducted in a restricted number of Mediterranean countries, having similar focuses, and employing similar research methods. This systematic map is based on a comprehensive and systematic screening of the scientific literature on the management of wildfire-related matters, written in English. It may assist managers and policymakers in identifying relevant studies addressing various management issues and consequently sparing them the effort to carry out a search fully from the beginning. It is also relevant for the academic community as it seeks to synthesize previous work and identify knowledge gaps to help direct future work. For example, a significant geographic gap in the studies across all MCRs was identified, and European work may serve as a reference to guide future research in other continents. It was also found that there has been limited research with a multidisciplinary focus and using methods to incorporate expert and practitioner knowledge, which ultimately could help shape integrated management schemes. Finally, even though there is considerable research involving all fire phases, more than half of the literature focused on pre-fire issues, and very few studies focused on emergency response or assessing the social, environmental, and economic losses linked to the fires. This unbalance may be one of the factors hindering progress in reducing wildfire occurrences and their impacts. Finally, the systematic map identified some areas with substantial research where systematic reviews or meta-analyses could be performed: preventive land and ecosystem management; fuels; fire behavior and risk modeling, and post-fire management.

2.5 References

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3 Wildfire environmental impacts: A comparison of the scientific findings, governmental concerns and experts' perceptions in Portugal

This chapter is based on the following work:

- R. Pacheco and J. Claro, “Post-wildfire Emergency Intervention in Portugal: an Analysis of Public Reports and Policy,” *Proc. Int. Conf. Environ. Sci. Appl.*, no. 118, pp. 1–6, 2020.
- R. Pacheco and J. Claro, “Perceptions of forest experts on the impact of wildfires on ecosystem services in Portugal,” in *ICEER2021 - 8th International Conference on Energy and Environment Research: “Developing the World in 2021 with Clean and Safe Energy,”* 2021.

3.1 Introduction

Fire plays a central role in the Earth system, particularly in forest ecosystems. This is especially relevant in Mediterranean regions considering their hot, dry summers [1]. In Europe, Portugal is the nation with the highest number of wildfires and the second with more burnt area [2]. The increasing occurrences of wildfires are turning post-fire forest management into an ever more critical topic [3], as over the past two decades, fires have increasingly affected human values, assets, and ecosystem services, such as air quality and long-term carbon storage [4].

Governments are often the ones to first respond in a wildfire event, either by directly combating it, or by assessing all the impacts that need to be mitigated in the short-term. In this sense, public reporting and transparency practices are believed to help in creating public value, as they are not merely a legal requirement for public managers but also a tool for interacting with stakeholders [5].

In Portugal, the Institute for Nature Conservation and Forests (ICNF, Portuguese acronym) assesses the main environmental impacts after significant wildfires, proposes emergency stabilization measures, and estimates their initial costs. This is performed following the guidelines presented in Order N. 9716-A/2017, from the Ministry of Agriculture, Forestry, and Rural Development. This information is publicized through reports that are accessible on ICNF's website [6]. The reports have the strategic objective of assisting in the mitigation of environmental impacts, particularly prior to the rainy

season, namely in terms of combating erosion, torrential correction and to prevent the contamination of water-bodies by debris [7].

In this context, examining the content of these reports may provide valuable insights regarding the main environmental impacts that need to be managed in the post-fire phase. In this sense, considering both the human and environmental dimensions of wildfire, the concept of ecosystem services is a useful framework for understanding wildfire and formulating viable land management strategies [8].

Ecosystem services are defined in The Economics of Ecosystems and Biodiversity (TEEB) as “the direct and indirect contributions of ecosystems to human well-being.” Among TEEB’s objectives is to understand better the economic significance of these services losses and the consequences of policy inaction on halting biodiversity loss at various scales. This framework provides both the scientific basis for the economics of ecosystems and biodiversity and results that are useful for policymakers, administrators, businesses, or consumers [9].

Understanding the nuanced roles that fire plays in ecosystem services in fire-prone landscapes is essential to portray the trade-offs between people’s needs and desires and the sustainability of complex socioecological systems [8]. It has been suggested that fire management could focus on shaping fire regimes, aiming to balance ecosystem services and natural resources protection [10]. However, the scientific literature linking fire to ecosystem services is still evolving, and disparate and relevant research often has not explicitly identified the roles that fire plays in “ecosystem services” [8].

Considering this context, the present work aims to characterize the wildfire impacts caused to the ecosystem services in Portugal. This is done through a triangulation approach. First, a systematic review of the literature is conducted to identify the scientific studies that address this matter in Portugal and examine their findings. Next, a document analysis is performed of all the emergency stabilization reports [6] and technical reports [11] available at ICNF’s website. Lastly, a survey directed to wildfire specialists is used to identify their perceptions of fire impacts. To standardize and allow the comparison of the impacts on the ecosystem services identified in all cases, TEEB’s definition of ecosystem services was applied [9]. Finally, the impacts found are compared with the environmental regulations in Portugal, and possible opportunities for cooperation among the scientific community and government agencies in the development of greener policies are discussed.

3.2 Material and methods

The first part of this study employs a methodological procedure based on the work of James et al. [12] for systematic mapping in environmental sciences, on the PRISMA (Preferred Reporting Items for Systematic Reviews) guidelines for systematic reviews [13] and other studies with similar scopes [14], [15]. In the following sections, the scope and specifics of this part of the study are explained.

In the second part, a document analysis is performed [16] on ICNF's emergency stabilization reports and technical reports to elicit the main ecosystem services impacted by the wildfires.

Next, a survey is directed to wildfire experts in Portugal to elicit their perceptions regarding the fire impacts and policies to address them.

Finally, a comparison is made between the concerns presented in the literature, the ones reported by ICNF, and those put forward by the fire specialists. All methodological procedures are presented in detail in the following sections.

3.2.1 Geographic scope

Portugal's mainland area is of approximately 89.000 km² and is located within the 37 °N and 42 °N latitudes and 6 °W and 10 °W longitudes. The mainland's altitude ranges from sea level to almost 2000 m in Serra da Estrela, being that the highest elevations are situated in northern and central Portugal [17].

The country is divided by the Tagus River into two regions of roughly the same size, being that they have different topographies and two subtypes of temperate climate. According to the Köppen-Geiger's climate classification [18], the two subtypes of Mediterranean climate in Portugal are Csa (dry and hot summer) to the south of the Tagus River and Csb (dry and warm summer) to the north [2]. The mean annual precipitation and temperature behave following a gradient of decreasing rainfall and increasing temperature from northwest to southeast. Mean annual rainfall varies from 400 mm to 2800 mm and annual temperature from 7 to 18 °C [17].

Forests and woodlands extend over one-third of the Portuguese landscape [17]. These forests comprise a broad range of ecosystems varying from intensive silviculture plantations for wood production to plantations for coastal dune protection and agroforestry systems [19]. Despite the climatic influences, over 80% of the forest area is dominated by four species: Maritime pine (*Pinus pinaster*), eucalypt, cork oak, and holm oak [17].

Since 1986 the Portuguese Government adopted the common standard for all member states of the European Commission, designated by the Nomenclature of Territorial Units for Statistics (NUTS). For this reason, the NUTS level II was adopted to structure the results of this study to reflect regional wildfire impacts. All the studies selected were from Continental Portugal, which is divided into 5 basic regions: North, Center, Alentejo, Algarve, and Lisbon Metropolitan Area. Figure 3-1 shows the location of the regions.



Figure 3-1 - NUT II regions in Continental Portugal.

In terms of agrarian structure, the country can roughly be divided into two major types. The North region is constituted predominantly of smallholding areas, while the Alentejo region has more latifundium areas [20]. Given the smaller and sometimes isolated nature of the properties in the North, many were abandoned for social and economic reasons through the years. The decline of agricultural activities in this region contributed to an increase in fuel accumulation and fire proneness of the landscape, which probably led to an increased number of fires when compared to other regions of the country [21].

3.2.2 Literature search

The search was focused on peer-reviewed studies that explicitly focused on issues related to wildfire impact assessment in Portugal. With that goal, Elsevier's Scopus (*title*, *abstract*, and *keyword* fields) and Thomson Reuter's Web of Science (*title* and *topic* fields) online databases were searched, as performed in other systematic review studies [15], [22]. The following search string was used in the databases: **fire; Portugal; impact**

assess*. The asterisk (*) was used in some search terms to expand the number of studies retrieved. For example, in the instance of “*fire,” studies including either “fire” or “wildfire” in one of the search fields are found.

3.2.3 Selection criteria

Once the searches were done, the title, abstract, and keywords of the studies were read to confirm that they were in alignment with the scope of this study. The inclusion criterion used to select the studies to be further investigated was: *Focused on Portugal and wildfire impact assessment*. The exclusion criteria were: *not about environmental impact assessments; not focused on Portugal; not focused on wildfire impacts; Social/Health focus; Climate change focus* (in which wildfires were treated only as a consequence); and *pre-fire focus* (meaning that the impacts assessed were not related to an actual fire event).

3.2.4 Data extraction

Once the screening phase was concluded, the full texts of the selected studies were retrieved and reviewed. Information was extracted from each paper following the analysis topics: *year of publication; place of study; research methods; timeframe of the study*, and *main ecosystem services affected*. Figure 2-3 shows the type of information gathered from each study, according to the topic of analysis.

Year of publication	• Years
Place of study	• NUTS II
Research methods	• 13 categories
Timeframe of the studies	• Years
Main ecosystem services affected	• Types described in The Economics of Ecosystem and Biodiversity (TEEB)

Figure 3-2 - Structure of the content analysis.

Coding systems were used in the analysis of the topics “place of study,” “research methods,” and “main ecosystem services affected.” For the place of study, as described previously, the coding was performed according to the NUTS II region where the study was conducted.

As for the “research methods” used in each study, the categories are based on the ones used in the systematic review conducted by Krajter Ostoić et al. [15], who performed a study with a similar scope.

Regarding the “main ecosystem services affected,” the types depicted in TEEB [9] were used to code the main environmental impacts addressed in each study.

3.2.5 Document analysis

Document analysis was used for the examination of ICNF reports. It is a systematic procedure used for reviewing or evaluating documents, such as institutional reports and public records. Institutional reports are potential sources of empirical data and can help in the uncovering of meaning, developing understanding, and discovering insights pertinent to the research problem. As a research method, document analysis is applicable to produce detailed depictions of a single program or policy [16]. For this reason, content analysis was employed to help in identifying the main environmental concerns after a wildfire in Portugal presented by ICNF.

Presently, ICNF has 122 emergency stabilization reports available on its website, the oldest is from 2010 and the newest from 2019 [6]. There are also three technical reports that deal with impacts over a more extended period (around three years after the fire) [11]. These reports were examined, and the main environmental impacts specified in each were extracted. Once again, the ecosystem services proposed by TEEB [9] were used to standardize the impact information.

3.2.6 Survey

Surveys are often used in studies that aim to elicit perceptions from expert groups, which allows their tacit knowledge to be brought to the academic environment [23], [24], and thus is an adequate method for the goal of the present study. The survey was conducted via an electronic form. It was sent to governmental and non-governmental institutions that are focused on forest-related issues, including wildfires. The respondents from these institutions are considered “wildfire experts” for the purposes of the present study.

The survey had an introduction to the questionnaire and two sections. The first described the respondent in terms of: *Institution* (in which they work); *Years working in the institution*; *Years of experience in the field of knowledge*; and *Position* (they occupy currently).

In the second section, a first set of two questions were asked: *From your perspective, which of the following ecosystem services are impacted by wildfires in Portugal in the short-term?*; and *From your perspective, which of the following ecosystem services are impacted by wildfires in Portugal, in the long-term (more than 3 years after the fire)?*. All the 22 TEEB ecosystem services were enumerated following these questions. A Likert scale was associated with each service, from which the respondents had to decide from 0 (no impact) to 5 (severe impact)

Lastly, to gain perspective on Portugal's current post-fire policy state, the following questions were asked: *For which of these services are there established guidelines to address the fire impacts? Select as many alternatives as you see fit.*; and *From your perspective, is there a lack of policies or guidelines to address the impacts on one of these services? Select as many alternatives as you see fit.* Once again, all 22 TEEB ecosystem services were listed, but for these questions "checkboxes" were employed, and respondents were instructed to choose as many services as they believed were relevant.

3.3 Results

The presentation of the results of this study has four main parts. First, the results of the systematic review are presented. In the second part, the document analysis characterizes the main environmental impacts identified in the 122 emergency stabilization reports currently available at ICNF's website [6], as well as three technical reports [11], in terms of the ecosystem services they disrupt [9]. Third, the results of the survey are presented and discussed. Finally, an overall analysis of the results is made, aiming to verify how aligned they are with the environmental regulations, as well as identify knowledge gaps and opportunities for cooperation towards the development of greener policies.

3.3.1 Systematic review of the literature

The search on the databases was conducted on February 2nd, 2020, and yielded 231 studies, of which 128 were found on Scopus and 103 on Web of Science. Once the duplicates were removed, a total of 151 studies remained to be screened by reading the abstracts and applying the previously defined inclusion and exclusion criteria. In this step, 94 studies were excluded. Most of them either did not focus on environmental impact assessments or were not focused on wildfire impacts, i.e., they focused on themes such as logistics or management, which are relevant but are not aligned with the scope of this

study. Finally, 57 studies were left for information extraction. Of those, 53 were retrieved, and three were excluded after reading the full text because they were mostly focused on the impacts of experiments or the use of a specific technology and not wildfires. The studies that were not found were either early studies (from the 1990s) or not included in the institutional subscriptions to which the authors had access. Figure 3-3 illustrates the process described above.

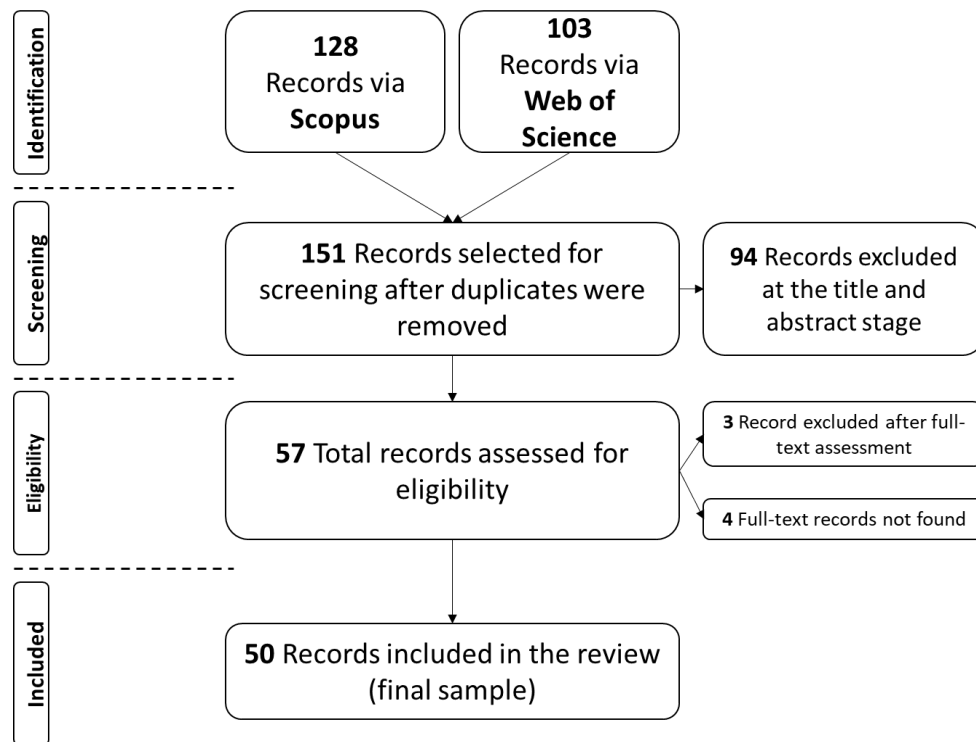


Figure 3-3 - The methodological approach used in the systematic mapping study, following an adapted version of the PRISMA guidelines [13].

Next, the main results from the 50 studies reviewed are discussed according to each topic of analysis. It should be highlighted that no systematic review studies were retrieved in this search, which underpins the novelty and relevance of this work. Studies that help to illustrate the findings are referenced throughout the discussion. For more details on the studies, please refer to Appendix B.

3.3.2 Year of publication and place of study

The time distribution of the publications is shown in Figure 3-4, and it spanned from 1996 till 2019. A level of consistency can be observed in terms of the number of studies in the last 10 years, being that the average number of publications is around five per year. It should be noted that the search on the databases was conducted in February of 2020, so studies from that year were not found.

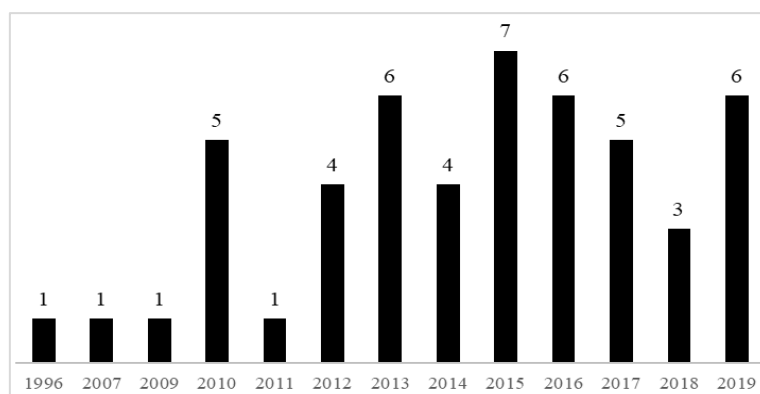


Figure 3-4 - Distribution of studies analyzed per year of publication (n=50).

Regarding the places of study, their distribution, according to the NUTS II region they focused on, is displayed in Figure 3-5.

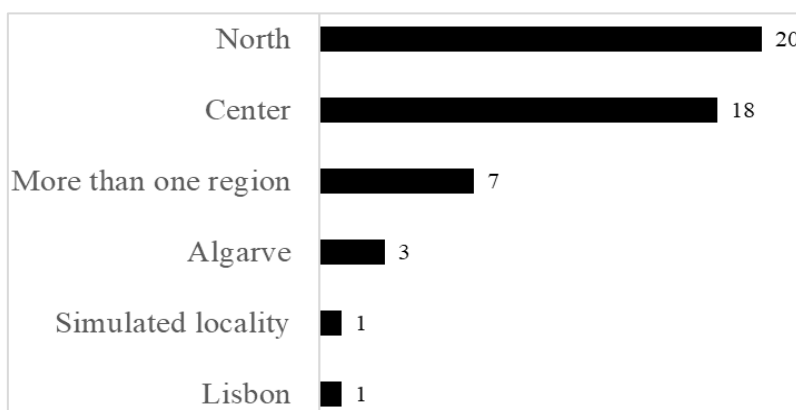


Figure 3-5 - Distribution of publications analyzed according to the NUTS II region the studies were conducted (n=50).

Most of the studies (76%) took place in the North and Center regions, which is to be expected since these locations tend to experience more fires due to the subtype of climate located at the north of the Tagus river [2]. Some studies (14%) addressed more than one region. This usually was the case when the impact analyzed transcended borders, such as the study of particulate matter and ozone levels during fire seasons [25] or fire impacts on air quality [26]. Also, a few publications studied more than one fire site to increase the statistical relevance and representativeness of their results [27]–[29]. Three studies were developed in Algarve, dealing mostly with the local ecosystem's concerns [30]. The one study developed in the Lisbon region was the only one retrieved that dealt with heavy metals released from ashes after a wildfire [31']. Finally, there was one study that simulated a locality to analyze the impacts of fire severity on the sustainability of eucalyptus forests in Portugal [32].

3.3.3 Research methods and timeframe of the studies

Regarding the research methods, Figure 3-6 shows the six categories employed by the studies. Most studies employed only one research method (31), while the others (19) used two methods. The single most used methods were “Field sampling and/or laboratory analysis” (18) and “Experiment (field, nursery, laboratory)” (14), which suggests that most studies had a practical nature that involved fieldwork. As for the studies that employed two methods, the most frequent combinations were “Modeling/simulation/scenario” with “Field sampling and/or laboratory analysis” (4) or with “Secondary data analysis (existing database & record analysis)” (4). This implies that studies require data to input in their modeling effort, and it was obtained either by collecting field data or using existing databases.

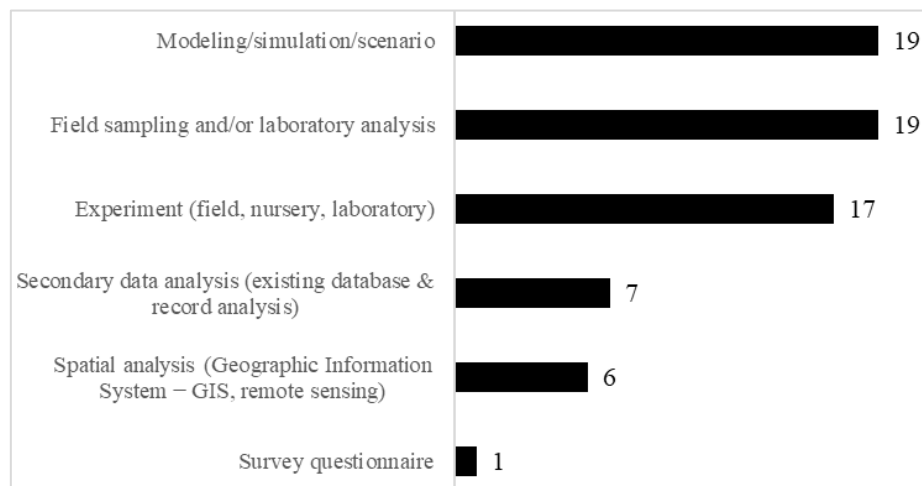


Figure 3-6 - Distribution of the research methods employed by the analyzed studies. Some studies used more than one research method.

It is noticeable that in terms of methodological approach, all but one study employed exclusively quantitative research methods, which are associated with rational and objective measurements of observable phenomena [33]. Only one of the analyzed studies used a questionnaire, which is a qualitative method, focusing on the assessment of subjective phenomena (e.g., ideas, opinions, patterns) [33]. This study had a more holistic approach, proposing a framework that conceptualizes fire impacts as a result of interaction between fire behavior, vulnerability, and suppression capabilities [34].

Regarding the timeframe, Figure 3-7 illustrates how long after the fire, the study was developed. Most studies (almost 50%) were conducted between one year and 10 years after the fire occurred. In this sense, most of the analyzed work (75%) had long-

term environmental concerns, such as land cover changes [35], [36], impacts on water sources, and hydrogeological cycles [37], [38], and land degradation [39], [40].

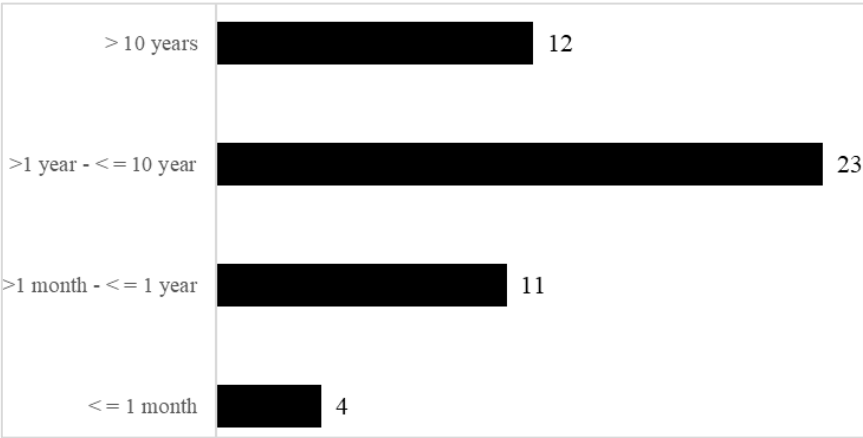


Figure 3-7 - Time after the fire that the studies were conducted (n=50).

The studies with short-term concerns (up to one year after the fire) were mostly focused on runoff and soil erosion [41]–[43]. Finally, the studies that were conducted very shortly after the fires aimed at examining impacts on air quality [44], managing the impacts in near real-time [45], or addressing the impacts of chemicals released by the ashes and fire [31], [46].

3.3.4 Main ecosystem services impacted

TEEB proposes a typology of 22 ecosystem services divided into four main categories; provisioning, regulating, habitat, and cultural & amenity services [9]. Figure 3-8 illustrates the categories of ecosystem services impacted by wildfires most studied by the literature analyzed.

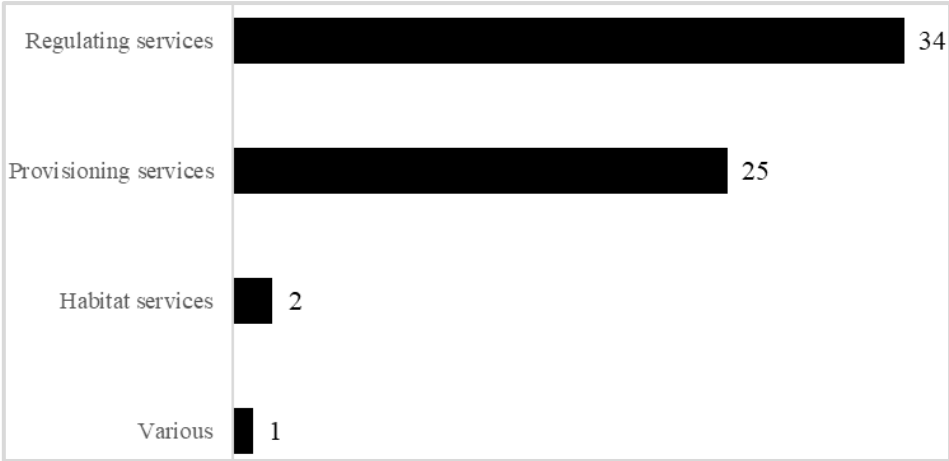


Figure 3-8 - Categories of ecosystem services impacted by wildfire most studied. Some studies addressed more than one ecosystem service impacted.

Regulating services, such as Erosion prevention and Maintenance of soil fertility, were among the most researched topics, followed by provisioning services, as Raw materials (Ex. wood) and Water. Habitat services were only addressed by two studies, while one study had a more holistic approach, examining various impacts, including social and managerial dimensions [34]. Figure 3-9 shows specifically, which were the impacts on the ecosystem services addressed by the studies.

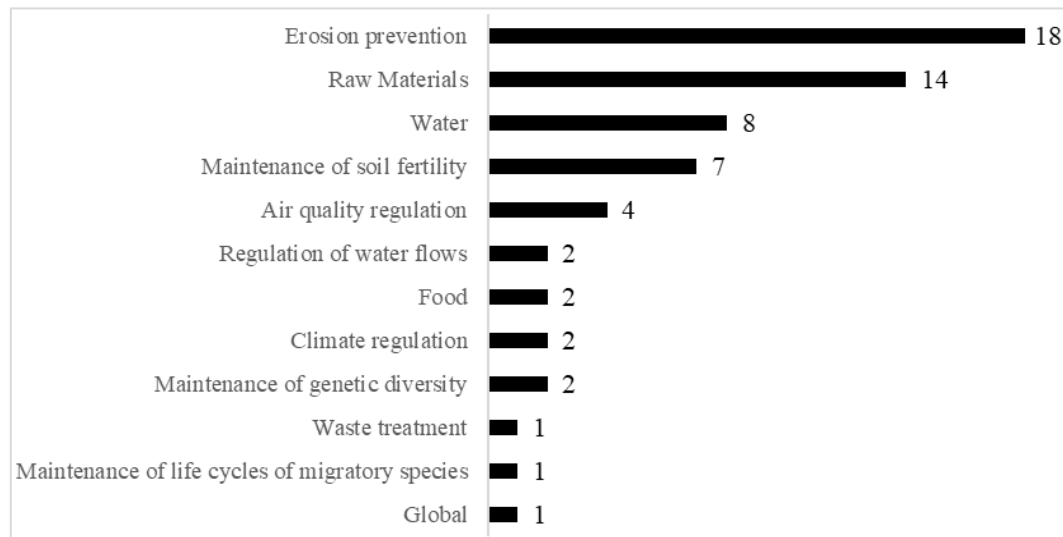


Figure 3-9 - Ecosystem services impacted by wildfire most studied. Some studies addressed more than one ecosystem service impacted.

The loss and mitigation of Erosion prevention services were among the most studied topics (18), as it is one of the most notable wildfire impacts [39]–[41], while the Maintenance of soil fertility was less studied (7) [47], [48]. The loss of Raw materials, mainly wood, was the second most studied topic, which is to be expected since it is one of the most notorious environmental impacts [19], [49].

The Water service, which concerns water for human consumption, was the third most studied topic (8), usually addressing the impact of fire-related pollutants on the quality of water [28], [46]. In contrast, the Regulation of the water flows, which is the hydrogeological cycle, was only explicitly the focus of two studies [50], [51].

Among the least studied topics were the Maintenance of genetic diversity, Maintenance of life cycles of migratory species, and Waste treatment, which were addressed by only one study each. Finally, it should be noted that none of the retrieved studies attempted to valuate the impacts that the fires had caused economically.

3.3.5 Content analysis of ICNF reports

The need for ICNF to prepare emergency stabilization reports and propose mitigation measures following each significant wildfire is instated by Order N. 9716-A/2017 from the Ministry of Agriculture, Forestry, and Rural Development. The legal document provides guidelines regarding the format and content of the reports, and the information is made public on ICNF's website [6]. Additionally, the content must be systematized based on uniform criteria and formats that should be functional, objective, and simple [7]. The 122 emergency stabilization reports currently available were analyzed [6]. A total of 4 reports were from Algarve, 9 from Lisbon, 48 from the North, and 61 from the Center. Figure 3-10 displays the number of reports available according to the year of the fire and region of the country.

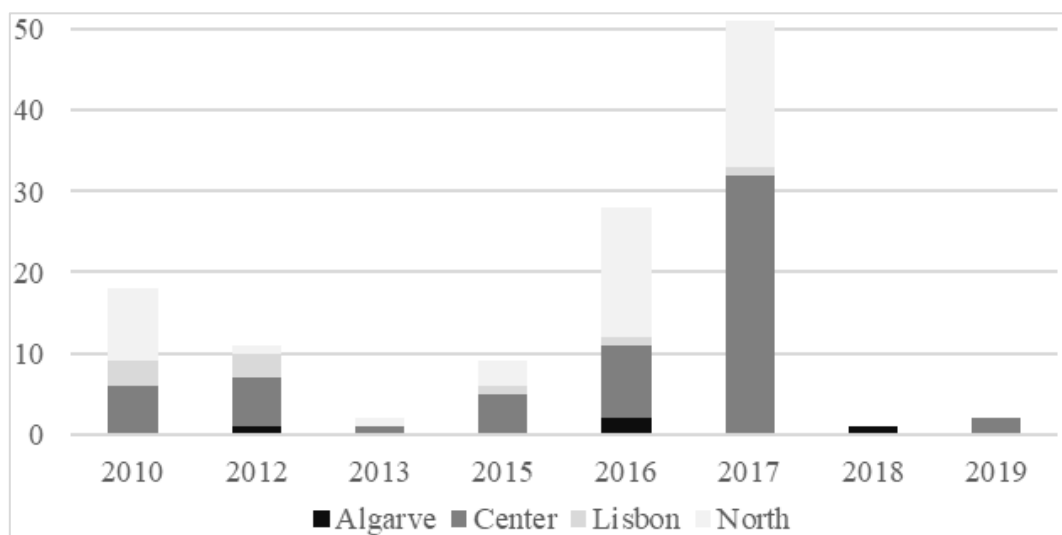


Figure 3-10 - Number of reports available by year, according to the region of the country.

Around 42% of the reports are from 2017, which is reasonable as that year experienced a record in the total burnt area [52]. Regarding the regions of the country, about 90% of the reports are about fires that happened in the North and Center regions, which is to be anticipated as these regions tend to experience more fires [53].

Regarding the identified ecosystem services disrupted due to the fire, Figure 3-11 shows a compilation of all the wildfire impacts cited in the reports. All reports mentioned losses in terms of Raw materials as timber was always impacted, even if the fire also happened on shrublands. Still, about the flora, many reports stated the concerns with the Maintenance of genetic diversity, as exotic and invasive species historically tend to take over impacted regions, reducing the genetic diversity of that ecosystem.

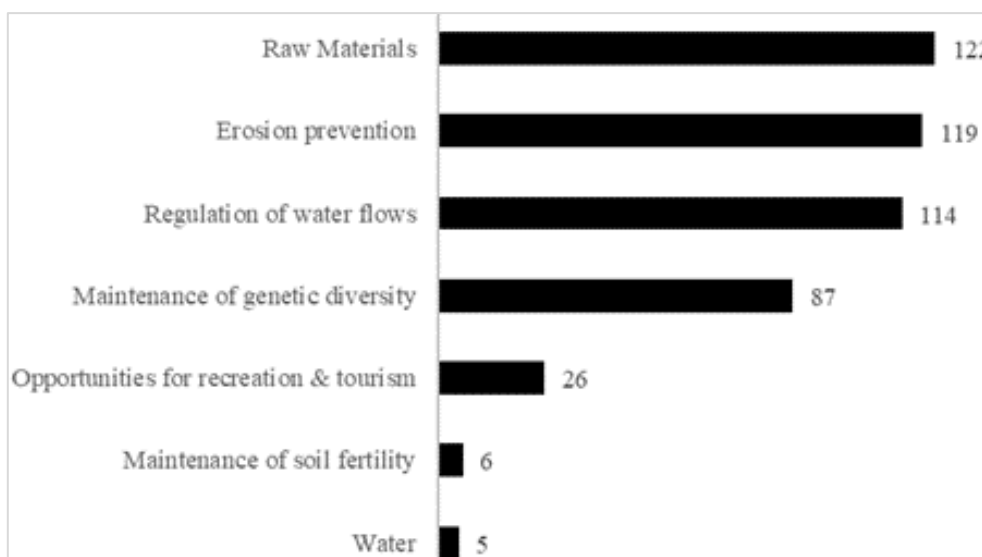


Figure 3-11 - Ecosystem services impacted according to the reports. Most reports identified more than one impact.

As for erosion, all but three reports acknowledged it to be a concern given the loss of the Erosion prevention service provided by the vegetation that covered the soil prior to the fire. In contrast, not many reports stated concerns with the Maintenance of soil fertility, associated with the loss of nutrients caused by precipitation after the fire, with the soil still exposed.

Regarding the impacts on water, most reports indicated to be concerned with the effect that the change in soil absorption properties would have on the Regulation of water flows. In addition to that, a few fires happened in areas that were near water abstraction sites for public supply. In these instances, the ecosystem service Water was affected, and mitigation measures were even more pressing as the fire had not only impacted the water cycles but also, more immediately, the supply for human consumption.

In fewer cases, hunting and ecotourism areas were impacted by the fires. As hunting in Portugal is mainly done for recreation and not as a primary source of food, the ecosystem service of Opportunities for recreation & tourism was the one that suffered losses. It should be noted that Order N. 9716-A/2017 only openly addresses three environmental impacts: erosion control, contamination of water lines, and biodiversity loss. In many cases, the reports included more impacts than those, which suggests that the experts were sensitive to other impacts, even if not enumerated in the official guidelines.

Lastly, to briefly analyze longer-term concerns, the three technical reports currently available were examined [11]. These technical reports deal with the timeframe

of three years after the fire, and the only impacts they mention are on the flora, in particular the loss of Raw materials and Maintenance of genetic diversity ecosystem services. This indicates that ICNF expects most environmental impacts to be tackled in the short-term. Erosion control, for example, usually needs to be rapidly addressed, whereas vegetation recovery, especially for timber, is a process that entails more time to be mitigated.

3.3.6 Expert perceptions on wildfire impacts

The survey was sent to three different institutions that are responsible for wildfire management and policy in Portugal. They were: ICNF; AGIF - Agency for Integrated Rural Fire Management, which has the institutional mission of “planning, strategic coordination and assessment of the integrated rural fire management system”; and ForestWISE, that is an institution with emphasis on interdisciplinary knowledge transfer that focuses on the problem of rural fires and the related issue of the valorization of forest (market and non-market) products and services. Some of the respondents were affiliated with other institutions as well, such as the University of Trás-os-Montes and Alto Douro (UTAD), and they filled the questionnaire as such. Figure 3-12 shows the first section of the questionnaire that characterizes the respondents of the survey.

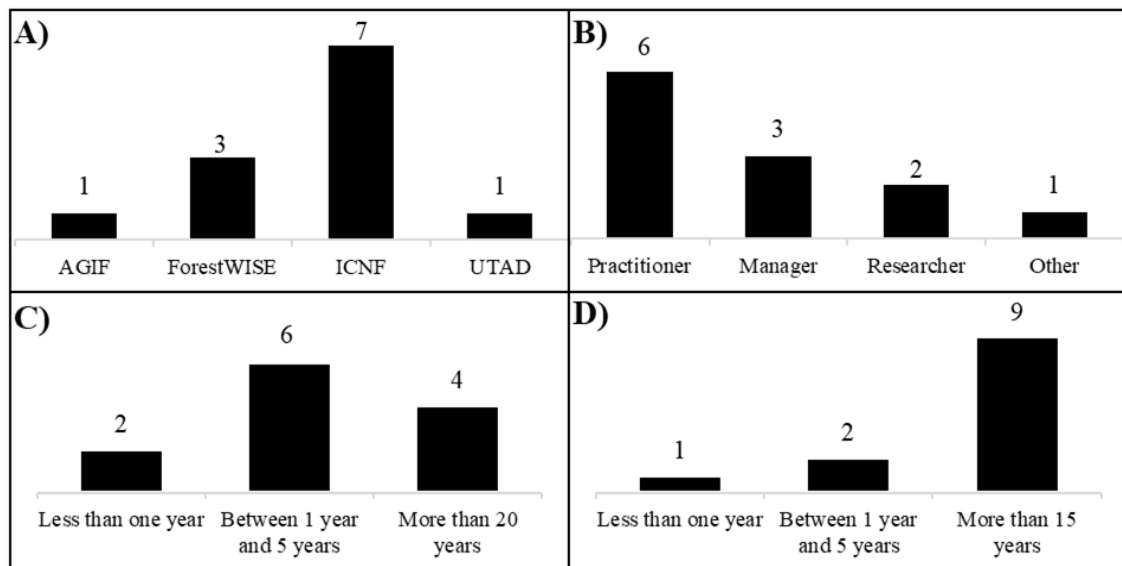


Figure 3-12 - Characterization of the 12 respondents. a) Institution of affiliation. b) Position occupied in the institution. c) Years working in the institution. d) Years working in the area.

The questionnaire was answered by 12 individuals. Most of the respondents are from ICNF (7) and are practitioners (6), that is, they work in the area and do not currently hold a manager position. Half of the respondents have been working somewhere between

1 and 5 years in the institution, but most (9) have more than 15 years of experience working with wildfires, which suggests that the majority of the respondents are experts in the field of wildfire management.

As for the second section, Table 3-1 shows the answers given for the two questions regarding the fire impacts to the forests' ecosystem services, both in the short and longer (more than 3 years after the fire) terms. As mentioned previously, in the Likert scale employed, "0" represents "No impact," and "5" represents "Severe impact."

Table 3-1 - Level of impact for each ecosystem service reported by the respondents for the short and long (> 3 years after the fire) terms. In the Likert scale used, "0" represents "No impact" and "5" represents "Severe impact." The percentages indicate the proportion of the respondents that chose that level of impact. The numbers highlighted in the table show the most chosen level of impact for each of the 22 ecosystem services.

		Short-term impacts						Long-term impacts					
		0	1	2	3	4	5	0	1	2	3	4	5
Provisioning	Food	0%	8%	8%	25%	58%	0%	0%	8%	17%	58%	17%	0%
	Water	0%	8%	25%	8%	42%	17%	8%	0%	25%	25%	42%	0%
	Raw Materials	0%	0%	17%	0%	25%	58%	0%	0%	0%	17%	33%	50%
	Genetic Resources	8%	17%	17%	33%	25%	0%	8%	17%	17%	25%	25%	8%
	Medicinal Resources	17%	8%	25%	17%	33%	0%	8%	17%	25%	25%	25%	0%
	Ornamental Resources	17%	33%	25%	17%	8%	0%	8%	25%	25%	33%	8%	0%
Regulating	Air quality regulation	0%	0%	17%	0%	50%	33%	8%	8%	17%	17%	50%	0%
	Climate regulation	0%	0%	0%	0%	58%	42%	0%	0%	0%	25%	75%	0%
	Moderation of extreme events	0%	0%	0%	17%	42%	42%	0%	8%	0%	33%	33%	25%
	Regulation of water flows	0%	0%	8%	17%	17%	58%	0%	8%	0%	25%	58%	8%
	Waste treatment	8%	0%	17%	17%	17%	42%	8%	0%	17%	33%	42%	0%
	Erosion prevention	0%	0%	0%	17%	42%	42%	0%	8%	8%	25%	42%	17%
	Maintenance of soil fertility	0%	0%	0%	33%	33%	33%	0%	8%	0%	25%	42%	25%
	Pollination	8%	0%	8%	25%	42%	17%	8%	8%	25%	42%	8%	8%
Habitat	Biological control	0%	0%	17%	8%	42%	33%	8%	8%	0%	33%	33%	17%
	Maint. of life cycles of migratory sp.	8%	0%	17%	17%	50%	8%	8%	8%	17%	42%	17%	8%
Cultural & Amenity	Maint. of genetic diversity	8%	0%	25%	25%	33%	8%	8%	0%	8%	58%	17%	8%
	Aesthetic information	0%	8%	8%	8%	42%	33%	8%	8%	17%	58%	0%	8%
	Opp. for recreation & tourism	0%	0%	8%	8%	50%	33%	0%	8%	17%	58%	8%	8%
	Inspiration for culture, art and design	8%	17%	17%	58%	0%	0%	8%	17%	8%	67%	0%	0%
	Spiritual experience	0%	25%	25%	42%	0%	8%	8%	33%	8%	50%	0%	0%
	Info for cognitive development	0%	17%	42%	25%	17%	0%	17%	17%	17%	42%	8%	0%

Table 3-1 highlights the most frequent level of impact answered by the respondents, according to the ecosystem service, both for the short- and longer-term impacts. In terms of Provisioning services, the impacts seemed to diminish somewhat over time but were mostly on the severe side even three years after the fire event. The impacts on the Raw material service stand out as one of the most meaningful and persistent, being that half of the respondents believe that the impact is still severe three years after the fire event. From that, it can be inferred that the loss of tree coverage is perhaps the most notorious fire impact, in the opinion of the experts, which is somewhat in alignment with the longer-terms reports from ICNF [11].

As for the Regulating services, they were overall the most impacted group in the short-term, being that most of the experts considered that they are a bit recovered in the period of three years following the wildfire. Regarding the Habitat services, most experts seemed to believe that even though they are quite severely impacted, they improve their condition in the period following the wildfire. The results regarding the Cultural & Amenity services are less obvious, as some experts indicated that the impacts are believed to increase over time, a few remain somewhat unaltered, while others seemed to deteriorate over time.

As for the last part of the survey, Figure 3-13 shows the answers to questions regarding the policies in place to deal with the ecosystem services lost due to fires and those that still lack policies.

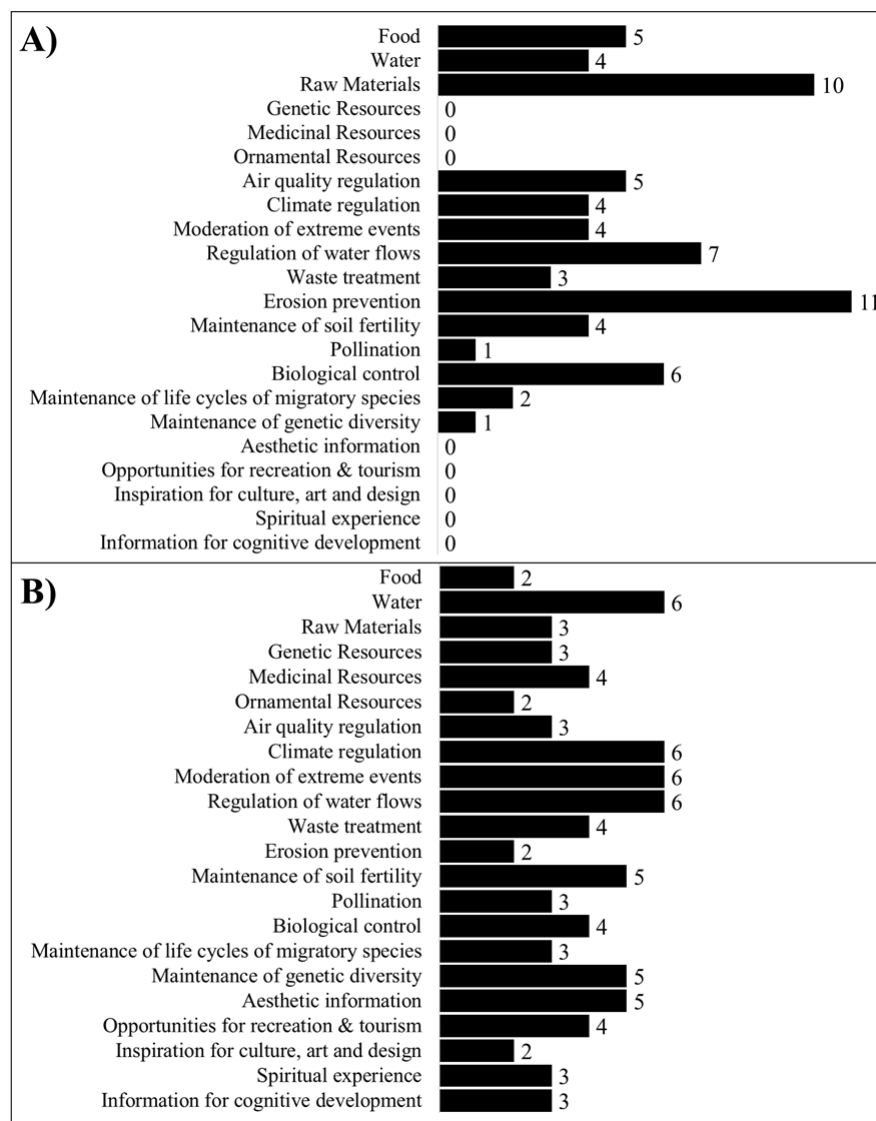


Figure 3-13 - Answers to the third and fourth questions of the survey. A) Refers to services with policies currently in place. B) Refers to services still lacking policies in the perception of the respondents.

Given the wide range of impacts and their persistence following wildfires, policies can play a vital role in restoring the environment. Figure 3-13 indicates the policy needs identified by the respondents. It is somewhat coherent that since all services were considered to be impacted by wildfires, all were deemed to need specific policies.

It can be highlighted that Regulating services seemed to be thought of as the group most in need of specific policies. This is coherent with the fact that this group was perceived as the most impacted by the wildfires, both in the short and long-term.

Despite the focus of this study being on fire impacts, these policies might not necessarily aim at recovering the impacted land. In this sense, European guidelines are shifting their focus from fire suppression to prevention and increasing the awareness and preparedness of populations at risk [54]. Therefore, it would make sense for environmental policy to follow the same trend as it is better to avoid fires and their impacts than mitigate them.

3.3.7 Comparison of the environmental impacts described in the literature, the reports, and survey

The literature review and the report analysis showed that both the scientific community and the experts have identified fire impacts on the ecosystem services in Portugal that need to be mitigated. The analysis of the scientific publications showed a total of 12 ecosystem services disrupted by wildfires. In contrast, the analysis of the reports revealed that ICNF identified seven ecosystem services impacts. Table 3-2 shows the ecosystem services disrupted in both analyses, according to the region of the country.

Table 3-2 - Ecosystem services impacted according to the scientific literature and ICNF's reports, by the region of the country.

Region	Algarve	Center	Lisbon	North
Scientific Literature	- Maintenance of genetic diversity - Raw Materials	- Erosion prevention - Maintenance of genetic diversity - Maintenance of life cycles of migratory species - Maintenance of soil fertility - Raw Materials - Waste treatment - Water	- Maintenance of soil fertility - Raw Materials	- Air quality regulation - Climate regulation - Erosion prevention - Food - Maintenance of soil fertility - Raw Materials - Regulation of water flows - Water

Region	Algarve	Center	Lisbon	North
ICNF Reports	- Erosion prevention - Maintenance of genetic diversity - Maintenance of soil fertility - Opportunities for recreation & tourism - Raw Materials - Regulation of water flows	- Erosion prevention - Regulation of water flows - Maintenance of genetic diversity - Maintenance of soil fertility - Opportunities for recreation & tourism - Raw Materials - Water	- Erosion prevention - Maintenance of genetic diversity - Opportunities for recreation & tourism - Raw Materials - Regulation of water flows - Water	- Erosion prevention - Maintenance of genetic diversity - Maintenance of soil fertility - Opportunities for recreation & tourism - Raw Materials - Regulation of water flows

Even though the literature addressed more impacts than the reports, when analyzing per region, that is not always the case. For the Algarve and Lisbon regions, the reports addressed more impacts than the literature. Perhaps these regions are less studied than the others, given that the Center and North regions historically tend to display more fires [2], [53].

The only impact addressed in every region in both analyses was on Raw materials. This is probably due to it being the most evident impact, with clear ecological and economic implications. Table 3-3 shows a compilation of the ecosystem services not addressed by the scientific literature and ICNF's reports according to the region of the country.

Table 3-3 - Ecosystem services not covered by the scientific literature and ICNF's reports, according to the region of the country.

Region	Algarve	Center	Lisbon	North
Missing in ICNF's Reports	--	- Maintenance of life cycles of migratory species - Waste treatment	- Maintenance of soil fertility	- Air quality regulation - Climate regulation - Food - Water
Missing in the scientific literature	- Erosion prevention - Maintenance of soil fertility - Opportunities for recreation & tourism - Regulation of water flows	- Regulation of water flows - Opportunities for recreation & tourism	- Erosion prevention - Maintenance of genetic diversity - Opportunities for recreation & tourism - Regulation of water flows - Water	- Maintenance of genetic diversity - Opportunities for recreation & tourism

Examining ICNF's side, it stands out most of the fire impacts not addressed are regulating services (Air quality regulation; Climate regulation; Waste treatment; Maintenance of soil fertility). The regulating services provide value due to their role in securing the reliability of service supply over space or time, which is related to the system's resilience to environmental shocks [9].

Regulating services are particularly crucial as they moderate the variability or uncertainty of the supply of provisioning and cultural services. They are, however, also particularly challenging to quantify and especially to value [9]. Perhaps this is the main reason that ICNF tends not to address them. As is established in Order N. 9716-A/2017, there is the need to estimate the costs to recover the damages caused by the fires, which would be particularly challenging in the case of regulating services.

As for the scientific literature side, once more, the regulating services (Erosion prevention, Maintenance of soil fertility, Regulation of water flows) are the least addressed. It does not necessarily mean that there were not any studies among the selected, but some services were conducted in a few regions of the country. Given that these services have been studied in some areas, but not in others, it suggests that the disparity between the regions is not linked to the absence of specific knowledge. Perhaps there is a lack of incentives, interest, or infrastructure to conduct this type of study in some parts of the country.

The cultural and amenity services, specifically Opportunities for recreation and tourism, have not been identified in the literature analyzed for this study. Cultural and amenity services refer to the aesthetic, spiritual, psychological, and other benefits that humans experience by contacting ecosystems. TEEB arranges these services in two main groups: (i) spiritual, religious, aesthetic, inspirational, and sense of place; and (ii) recreation, ecotourism, cultural heritage, and educational services [9]. Even though Opportunities for recreation and tourism are ecosystem services, perhaps no studies were retrieved on this topic as they could have been addressed in more economic contexts and not in environmentally-focused publications.

Overall, in both contexts, it seems that impacts on regulating services are the least addressed subject, maybe due to the challenges associated with their quantification and valuation. Perhaps it is here where there are more opportunities for cooperation among the scientific community and experts. Frameworks that estimate the costs of wildfire impacts can be valuable analytical tools for providing detailed and transparent

information for the development of mitigation strategies and decision-making policies [55].

Lastly, despite not having asked to specify the answer according to the region of the country, the survey elicited that the experts believe that all ecosystem services are impacted, both in the short and long term, with no exceptions. All services are affected with varying levels of damage, and some recover more quickly than others. This perhaps indicates that science has by no means fully addressed the consequences of wildfire impacts, and perhaps the reporting system from ICNF needs to be more thorough. It should be noted that in the long-term, ICNF's concerns were centered on the flora. Most of the retrieved studies were conducted on the horizon of 1 to 10 years after the fire, which could be considered long-term, and most of them addressed impacts on other ecosystem services, such as Erosion prevention and Regulation of water flows. Both the survey results and the literature suggest that there are other long-term impacts that ICNF needs to address besides the ones on the flora.

Finally, there are services, such as Air quality regulation and Climate regulation, which are among the priorities of many European environmental agendas [56], [57], and are not reported by ICNF. Developing methods and metrics to quickly, even if roughly, assess the impacts caused by wildfires could be helpful for payment for ecosystem services schemes. Having a monetary value reference for the ecosystem losses can be useful to create incentives for landowners to finance the recovery of their properties or implement other environmental programs.

3.4 Conclusions

The literature review performed showed that in Portugal, a vast number of impacts to ecosystem services associated with forest fires have been studied. However, not every region of the country has been studied in the same level of detail. Also, considering that the focus of our search was impact assessment, studies dealing with the monetary valuation of the impacts were expected, but none were retrieved.

From a governmental perspective, Portugal currently has a government agency clearly assigned to deal with forest fire impacts and a sound legal framework to instruct emergency actions. However, some relevant impacts identified in the literature, such as Climate regulation, a central topic in the European environmental agenda, were not addressed by ICNF, not even in the long-term.

Lastly, from the experts' perspective, all the 22 TEEB ecosystem services are significantly impacted both in the short and long term. ICNF seems to focus more on the services that require fast engineering interventions to be mitigated in the short-term to avoid even further impacts and losses. However, tools that help them tackle services such as climate regulation could be very useful in perhaps help avoiding or reducing wildfire incidence and intensity in the first place.

There is still a long way ahead towards a greener society, and maintaining and recovering ecosystem services is considered a vital component of this journey. Developing more methods for an expedite valuation of the ecosystem services lost due to wildfire can be extremely useful in this context. In this sense, the present work contributed by showing knowledge gaps and opportunities for cooperation between the academic community and practitioners to further boost and support environmental protection programs in Portugal.

3.5 References

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4 Carbon policy as a means to address climate change, and prevent wildfires and biodiversity loss in Portugal

This chapter is based on the following work:

- R. Pacheco and J. Claro, “Prescribed burning as a cost-effective means to tackle climate change in Portugal,” in *12th Industrial Engineering and Management Symposium*, 2021, pp. 42–43.
- R. Pacheco and J. Claro, “Carbon Policy as a Strategy to Jointly Address Climate Change, Prevent Wildfires and Biodiversity Loss: A Portugal Case Study,” in *Proceedings of the 2nd International Conference on Environmental Science and Applications (ICESA’21)*, 2021, no. 115, pp. 1–7.
- R. M. Pacheco, “Carbon taxation as a means to incentivize forest and fire management,” *Environ. Dev. Sustain.*, 2021.
- R. M. Pacheco and J. Claro, “Prescribed burning as a cost-effective way to address climate change and forest management in Mediterranean countries,” *Ann. For. Sci.*, vol. 78, no. 4, 2021.

4.1 Introduction

Wildfires are a component of the Mediterranean Basin’s ecology; however, fire occurrence has been increasing and is likely to become more prevalent in the future due to climate change [1]. Forest fires change carbon sequestration by terrestrial ecosystems, and their emissions directly impact carbon cycles by increasing the atmospheric carbon dioxide (CO₂) [2], [3]. Forests can help tackle climate change by reducing greenhouse gas emissions and increasing greenhouse gas absorption, acting as a carbon sink, accumulating, and storing carbon-containing chemicals for indefinite periods. There is an increasing agreement among the participating countries and organizations of the United Nations Climate Conference that forestry is an effective means to mitigate climate change [4].

Climate change adaptation is no different from disaster risk reduction, and measures to tackle it should align with other sustainable development policies [5]. In this context, various global policies address the concerns that arise from climate change and the upsurge in forest fires, such as the United Nations Sustainable Development Goals (SDGs), specifically Goal 13 – Climate Action and Goal 15 – Life on Land, which are

related to climate regulation and biodiversity issues [6]. Implicit in the SDGs logic is that the goals rely on each other [7] and should be managed in a coordinated fashion.

In the European domain, these goals are transcribed into policies, such as the European Green Deal, which openly deal with the issue of climate change, and the EU Biodiversity Strategy for 2030, which seeks to direct Europe's biodiversity to a path of recovery by 2030, with benefits for people, the climate, and the planet [8]. As is acknowledged by the European Commission, the biodiversity crisis and the climate crisis are intrinsically associated. Climate change accelerates the destruction of the natural world through more extreme meteorological events, including wildfires, while the loss and unsustainable use of ecosystems are drivers of climate change [8].

Wildland fires are progressively becoming a substantial problem in several European nations. They impact ecosystems and societies and potentially induce global atmospheric problems, being that in the Mediterranean countries, forest fires are more frequent than in other regions in Europe [2]. In this scenario, despite the country having had a late raise in awareness of environmental concerns [9], Portugal is viewed as an interesting case study for forest-management interventions [10], as it is a characteristic representative of the Mediterranean region.

In agreement with the European guidelines, Portugal has established policies to tackle climate change, wildfires, and biodiversity recovery in recent decades. Portugal signed the Kyoto Protocol in 2002, and in 2005, through Resolution of the Council of Ministers (RCM) N. 68/2005, has established the National System of Inventory of Emissions by Sources and Removal by Sinks of Air Pollutants, which was later restructured by the RCM N. 20/2015. This data is used as the foundation for the annual National Inventory Reports (NIR) that are made public under the Kyoto Protocol. Still, regarding Climate Change, RCM N. 56/2015 approved the Strategic Framework for Climate Policy, the National Program for Climate Change, and the National Strategy for Adaptation to Climate Change. In the context of emissions, Law N. 82-D/2014 changed environmental fiscal norms and instated the Addition Tax on Carbon Emissions applied over specific energy sources. The revenue from this taxation is directed to the Portuguese Environmental Fund (created by Decree-Law N. 42-A/2016), which was conceived to sponsor sustainable development measures in the country.

Regarding wildfires, the RCM N. 59/2017 approved the National Prescribed Burning Program, seeking to reduce the fire events' extensions. This policy is not only beneficial in avoiding losses in terms of biodiversity, real state, and potentially lives, but

prescribed burning has been shown to reduce overall fire emissions in some Mediterranean countries, like Portugal [1], [2].

The rising number of forest fires in recent decades has been negatively impacting biodiversity in Portugal [9]. With regard to legislation, following the European directives, RCM N. 55/2018 approved the National Strategy for Nature Conservation and Biodiversity 2030, which acknowledges that forest fires endanger biodiversity, stating that Portugal should be in the vanguard in economically valuing ecosystem services. In this sense, RCM N. 121/2019 instated the first Ecosystem Services Payment Program in Rural Spaces in the country. This policy seeks to recognize the many important contributions of forests that are not valued by common markets, such as erosion control, carbon sequestration, regulation of the hydrological cycle, biodiversity conservation, fire susceptibility reduction, and landscape quality improvement. Figure 4-1 illustrates how the SDGs have been transcribed into European Policies and then to their Portuguese counterparts. The legislation enumerated is not exhaustive but comprises the parts that are most impactful in this study's scope.

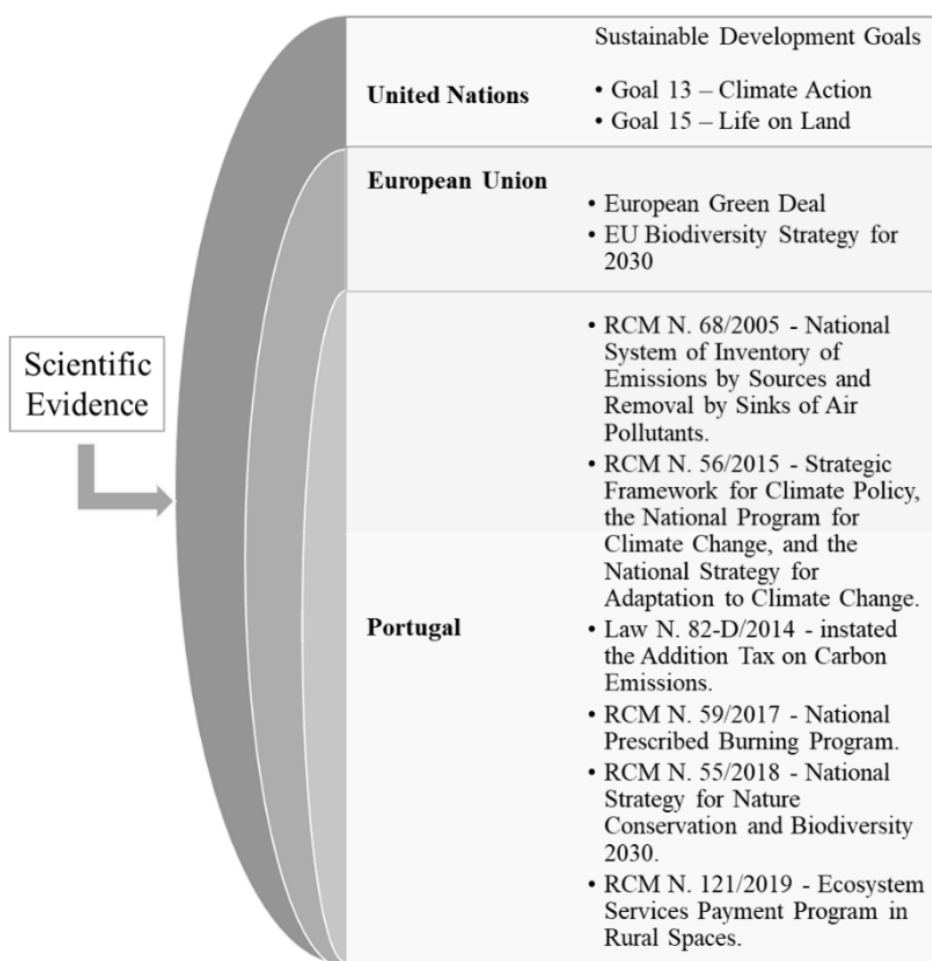


Figure 4-1 - Framework of policies related to climate change, wildfires, and biodiversity in Portugal.

These policies are founded on the growing scientific evidence and understanding of climate change and forests' role in carbon cycles. In this sense, policy-makers are experiencing new pressures to amend forest policies to include both climate change mitigation and adaptation [11]. However, to materialize actions to decrease CO₂ emissions by forests, landowners need to be fairly rewarded through economic incentives [12]. It is recognized that by institutionalizing incentives for carbon sequestration, for example, a more robust economic rationale can be made for amplifying forest restoration efforts [13]. In this context, carbon taxation has been suggested as a means to fund forest conservation measures around the world [14]. It has been demonstrated that forest carbon policies can be incorporated into an emission trading scheme [15] and that climate change and forest policies, both for adaptation and mitigation, can be addressed mutually through new governance arrangements [16].

Portugal has a robust regulatory framework related to climate change, biodiversity, and forest fire management, and there is literature supporting that a tax on fossil fuels can back the restoration of ecosystems that help curb climate change [14]. In this context, the objective of this study is to evaluate the newly established carbon taxation in Portugal as a means to incentivize forest restoration and fire management measures by comparing the carbon emissions savings by avoided fires and the income of the carbon taxation with the costs of prescribed burning and the payment for ecosystem services scheme. To achieve this, the most recent emission data available from the National Inventory Reports [17] is used, as well as the Addition Tax on Carbon Emissions from 2016 to 2020, and the prescribed burning scenarios proposed in the work of Vilén and Fernandes (2011). Furthermore, this study is relevant for a broader audience, as Portugal has been considered an interesting case study in the western world for forest-management related issues [10] and as other countries in the Mediterranean Basin have been shown to potentially reduce wildfire emissions by implementing prescribed burning policies [1], [2].

4.2 Methods

4.2.1 Approach

There is no "one size fits all solution" for examining public policies and their synergies. To evaluate the viability of using the newly established carbon taxation in Portugal to incentivize forest restoration and fire management measures in the country,

the analysis framework presented in Figure 4-2 was used. It is designed to provide an overview of the advantages of combining the policies regarding climate change, biodiversity conservation, and wildfire management in Portugal, which is believed to be beneficial for other countries, especially in the Mediterranean region.

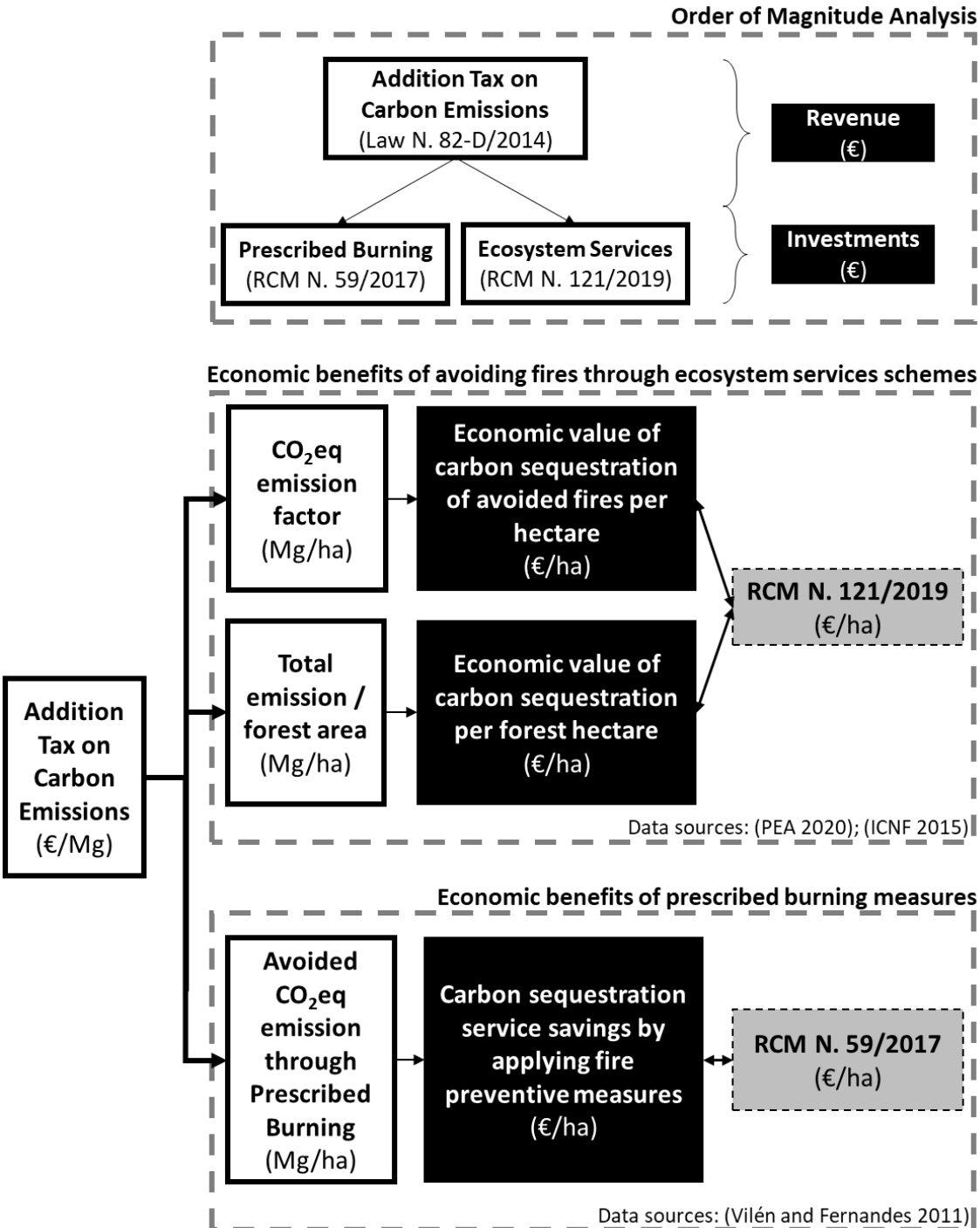


Figure 4-2 - Analysis framework employed. The white boxes represent data input, the black boxes the results of the calculations, and in grey boxes are the legislation or economic metrics used to compare and discuss the results.

The analysis is divided into three parts, though all rely, directly or indirectly, on the evolution of the value of the Addition Tax on Carbon Emissions (instated by Law N. 82-D/2014). In the first part (top of Figure 4-2), an order of magnitude analysis is performed to contrast the revenue from the Addition Tax on Carbon Emissions (Law N. 82-D/2014) against the investment needed for policies RCM N. 59/2017 and RCM N. 121/2019.

In the second part (middle of Figure 4-2), the economic benefits of avoiding fires through ecosystem services schemes are analyzed. This approach is similar to that employed by Matzek et al. (2015), who analyzed the viability of using carbon credits to fund forest restoration. For this, the annual wildfire emissions data from the Portuguese National Inventory Report on Greenhouse Gases, 1990 – 2018 [17] was used to estimate the carbon that would remain sequestered per hectare by avoiding these fires. The total vegetation area determined in the latest Portuguese national forest inventory [19] is also used to estimate the benefit associated with forest management. Lastly, these results are then compared to the economic incentive awarded by RCM N. 121/2019 to pay for the forest's ecosystem services.

The third part of the analysis (bottom of Figure 4-2) is based on the work of Vilén and Fernandes (2011). The authors demonstrated the potential benefits of prescribed burning measures in reducing forest fires' overall emissions in Mediterranean Basin countries. The current analysis is centered on the economic benefits that can be expected on a yearly basis, assuming that prescribed burning interventions are occurring in a steady state. These results are then compared with the prescribed burning costs presented in the National Prescribed Burning Program (RCM N. 59/2017). In the subsequent sections, the data sources used are shown, along with the performed calculations and the pieces of legislation used to discuss the results and their reference values.

4.2.2 *Order of Magnitude Analysis*

An order of magnitude analysis offers an efficient integration of quantitative and qualitative knowledge in the expression and resolution of engineering problems. The order of magnitude analysis is founded on seven primitive relations among absolute magnitudes of quantities: “much less than” ($\ll$), “moderately less than” ($\sim\ll$), “slightly less than” ($\sim\sim\ll$), “equal to” ($=$), “slightly greater than” ($\sim\sim>$), “moderately greater than” ($\sim>$), and “much greater than” ($\gg$) [20]. It provides a preliminary approximation of the

problem, serving as an outline to model the situation under study. The structure of the order of magnitude analysis used in this study is shown in Figure 4-3.

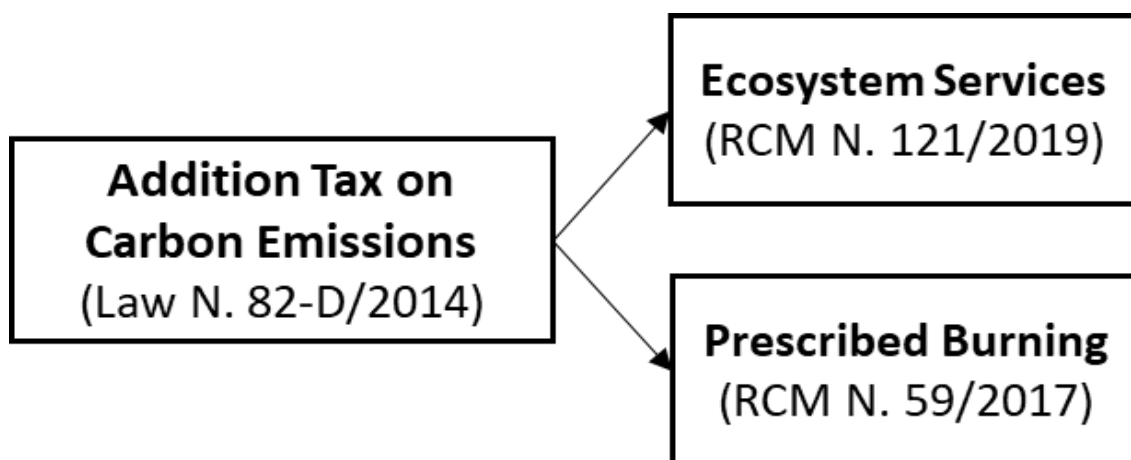


Figure 4-3 - Structure of the order of magnitude analysis.

The Addition Tax revenue (Law N. 82-D/2014) was obtained for 2016 until 2018 in a report from the Technical Unit of Budget Support (UTAO, 2019). The cost of the Payment for Ecosystem Services policy was retrieved in Notice N.13655/2019 (associated with RCM 121/2019), which accounts for the entire extent of the policy from 2019 until 2038. As for the prescribed burning policy, its costs for 2017 and 2018 are estimated in the National Prescribed Burning Plan (ICNF, 2017), a component of the National Prescribed Burning Program (RCM N. 59/2017).

4.2.3 *Emission Factors*

There are various methods to directly or indirectly quantify forest carbon sequestration [21]. For this study, to represent the carbon sequestered by avoiding fires in the Portuguese forests, the CO₂ equivalents emission factor per hectare was used. It is assumed that fire preventive initiatives could avoid these emissions and that these carbon equivalents would still be stored in the forest's biomass.

The data from Table 4(V) of the Common Reporting Format from the Portuguese National Inventory Report on Greenhouse Gases, 1990 – 2018 [17] was used to calculate the average CO₂ equivalents emission factor per burnt forest hectare for each reported year. This was done by adding the implied emission factor of every reported gas (in Mg/ha) times their global warming potential (100-year time horizon, as is done in the report). This calculation was done for every report year, following the equation:

$$\text{Average emission factor } \left(\frac{Mg}{ha}\right) = CO_2 \times 1 + CH_4 \times 25 + N_2O \times 298 \quad (1)$$

The variation of the average emission factors through the reported years is shown in Figure 4-5.

4.2.4 Emissions per Forest Area

Multiplying the average emission factors by the burnt area [17] provides an estimate of the total emissions from forest fires for every report year:

$$\text{Total emissions (Mg)} = \text{Average emission factor } \left(\frac{Mg}{ha}\right) \times \text{Burnt area (ha)} \quad (2)$$

Considering that the emissions result from the country's overall management of its forest area and stochasticity in individual locations and extensions of forest fires, we also compute the average emissions per area of forest, which can be understood as the outcome of that management. In addition to stochasticity, by considering all the forest area, instead of just the burnt area, this outcome measure also takes into consideration important externalities, such as the fact that well-managed areas can burn because of fires in neighboring (well-managed or unmanaged) areas, and the fact that unmanaged areas can escape burning because of neighboring well-managed areas.

Using estimates of the national forest area provided by the National Institute of Statistics [17] for 1995, 2005, 2010, and 2015, and linear interpolations between those years, the average emissions per area of forest can be calculated for every report year as follows:

$$\frac{\text{Average emissions per forest area}}{\left(\frac{Mg}{ha}\right)} = \text{Total emissions (Mg)} / \text{Forest area (ha)} \quad (3)$$

These results are used to calculate the carbon savings by forest management, presented in the following sections.

4.2.5 Carbon Value

To estimate the monetary value of the carbon sequestration service provided by avoiding fires in the Portuguese forests, the Addition Tax on Carbon Emissions was used

as the reference. Table 4-1 shows the values this tax has had since 2016, the year it started, until 2020.

Table 4-1 - Variation of the Addition Tax on Carbon Emissions.

Year	Addition Tax on Carbon Emissions (€/Mg of CO₂)	Source
2016	6.67	Ordinance N. 420-B/2015
2017	6.85	Ordinance N. 10/2017
2018	6.85	Ordinance N. 384/2017
2019	12.74	Ordinance N. 6-A/2019
2020	23.619	Ordinance N. 22/2020

According to Law N. 82-D/2014, the value of the tax for each year (n) is calculated in the previous year (n-1) as the arithmetic mean of the price resulting from auctions of greenhouse gas emission allowances, conducted within the framework of the European Union Emissions Trading System (EU ETS), between July 1st of year n-2 and June 30th of year n-1. This tax is applied over petroleum and specific energy sources, and the revenue collected is directed to the Portuguese Environmental Fund.

Carbon markets are a popular and cost-effective tool to mitigate CO₂ emissions. However, its creation is a learning-by-doing process and needs consistent regulatory updates to produce optimal effects, which has been transpiring since 2005 in the EU ETS [22]. Recently, following The Paris Climate Conference (COP21) context, the prices of carbon permits have been reaching all-time highs after EU leaders made a deal on more ambitious emissions cuts for this decade [23]. This is mirrored in the increasing Addition Tax values observed through the years.

4.2.6 Carbon Savings by Avoiding Fires

To estimate the economic value of the carbon sequestration service provided annually by avoiding fires in the Portuguese forests by hectare, the highest, the mean, and the lowest average emission factors per hectare reported were multiplied by the Addition Tax values. This approach resembles the one used by Matzek et al. (2015), who employed the California auction reserve price of a ton of CO₂e to estimate the potential income associated with the carbon sequestration service provided by restoring riparian vegetation. In the present study's case, instead of directly estimating the growing forest biomass as was done by these authors, the carbon emission data was used to estimate the biomass losses that could be prevented by avoiding fires. These calculations were

conducted for all Addition Tax values to show the temporal variation of the value of this service, following the equation:

$$\text{Carbon savings } \left(\frac{\text{€}}{\text{ha}}\right) = \text{Average emission factor } \left(\frac{\text{Mg}}{\text{ha}}\right) \times \text{Addition tax value } \left(\frac{\text{€}}{\text{Mg}}\right) \quad (4)$$

These results are shown in Figure 4-6.

4.2.7 Carbon Savings by Forest Management

This metric is used to represent the outcome of forest management practices. The extremes and mean Average emissions per forest area are used to estimate the carbon savings derived from forest management measures and is calculated as follows:

$$\frac{\text{Carbon savings}}{\text{from forest management}} \left(\frac{\text{€}}{\text{ha}}\right) = \frac{\text{Average emissions}}{\text{per forest area}} \left(\frac{\text{Mg}}{\text{ha}}\right) \times \text{Addition tax} \left(\frac{\text{€}}{\text{Mg}}\right) \quad (5)$$

These results are presented in Figure 4-7 in the results section.

4.2.8 Prescribed Burning Savings

To estimate the monetary savings of avoided emissions per hectare that prescribed burning measures could have in Portugal, the scenarios studied in the work of Vilén and Fernandes [1] are analyzed. They used published data to quantify the average annual wildfire CO₂ emissions in the country, following the Intergovernmental Panel on Climate Change (IPCC) guidelines, and estimated the effect that prescribed burning would have on the final emissions for four scenarios of treatment effectiveness based on data from Portugal.

To create these scenarios, the authors used empirical data and simulation to identify the extreme burn leverages by distinguishing between ecoregions exhibiting low (mean annual burned area <2%) and high (mean annual burned area >5%) incidence of fire. Where wildfire incidence was low, they assumed a 1 ha decrease in the area burned by wildfire for each treated ha, meaning that the likelihood of a wildfire encountering a previously burned area is low. Where wildfire incidence is high, they assumed a 3-ha wildfire area decrease per ha treated, as the spatial pattern of prescribed burning is optimized.

This information was then blended with the effects of two levels of prescribed burning treatment efforts, respectively 2 and 20% of the mean annual area burned by

wildfire. According to the authors, this reflects the current degree of prescribed fire development in Portugal and in France, respectively.

Table 4-2 summarizes the four scenarios and results in terms of emission reduction obtained in their study.

Table 4-2 - Scenario's description and calculated overall emission reductions in Portugal. Adapted from: Vilén and Fernandes (2011).

Scenario	Description	Emission Reduction
I	2% of the annually burned area treated by prescribed fire, assuming 1 ha decrease in the area burned by wildfire for each treated ha	1%
II	2% of the annually burned area treated by prescribed fire, assuming 3 ha decrease in the area burned by wildfire for each treated ha	5%
III	20% of the annually burned area treated by prescribed fire, assuming 1 ha decrease in the area burned by wildfire for each treated ha	13%
IV	20% of the annually burned area treated by prescribed fire, assuming 3 ha decrease in the area burned by wildfire for each treated ha.	52%

The annually burnt area calculated in this study is 109,327 ha (the average burnt area between 1980 and 2008), and the annual average CO₂ emissions in wildfires is 4,408,808 Mg.

Their results demonstrated that prescribed burning could have a substantial effect in reducing wildfire emissions in Portugal. Still, they acknowledge that the uncertainty in emission estimates is significant, and more accurate input data for the models, such as deadwood and litter, is needed.

To convert these emission reductions to the monetary savings they represent, the emission reduction in every scenario is multiplied by the Addition Tax value for every year, according to the following equation:

$$Treatment\ Savings\ (\frac{€}{treated\ ha}) = Emission\ savings\ (\frac{Mg}{treated\ ha}) \times Addition\ tax\ value\ (\frac{€}{Mg}) \quad (6)$$

These results are shown in Figure 4-8.

4.2.9 Uncertainties

The main uncertainties that affect the results of the present study derive from the base studies. Both the National Inventory Report and the work of Vilén and Fernandes (2011) estimate the uncertainties according to IPCC guidelines [24]. In the National Inventory Report, there were years with abnormally high final estimates of uncertainty that coincide with years for which annual net-emissions are close to zero, but for most years, the uncertainty of the overall emission was much lower [17]. This uncertainty affects the average emission factor calculated for every year. This uncertainty is addressed

with the presentation of the extreme values (maximum and minimum) and the mean value of the emission factor through the years to exemplify the range of possible values. As for Vilén and Fernandes (2011) study, the uncertainty in wildfire emission estimates is in the order of $\pm 58\%$. According to the authors, this uncertainty is linked to the lack of data for all fuel compartments and corresponding combustion factors. This uncertainty is discussed together with the results it affects in the following sections.

4.3 Results and Discussion

4.3.1 Magnitude of Revenues and Investments

As is acknowledged by the European Commission, the biodiversity crisis and the climate crisis are intrinsically linked. Climate change accelerates the degradation of the natural world through more extreme climatic events, such as wildfires, while the loss and unsustainable use of nature are drivers of climate change [8]. Under these harsher climate conditions, it is expected that present fire suppression strategies cannot control all wildfires, and its ability to do so might be compromised [25]. This supports the argument to proactively invest in wildfire prevention through prescribed burning and fund biodiversity conservation measures. Next, the results of the order of magnitude analysis and economic benefits of the National Prescribed Burning Program are shown.

The revenue from the Addition Tax and the investments needed for RCM N. 59/2017 and RCM N. 121/2019 are presented in Figure 4-4, displaying the order of magnitude analysis conducted.

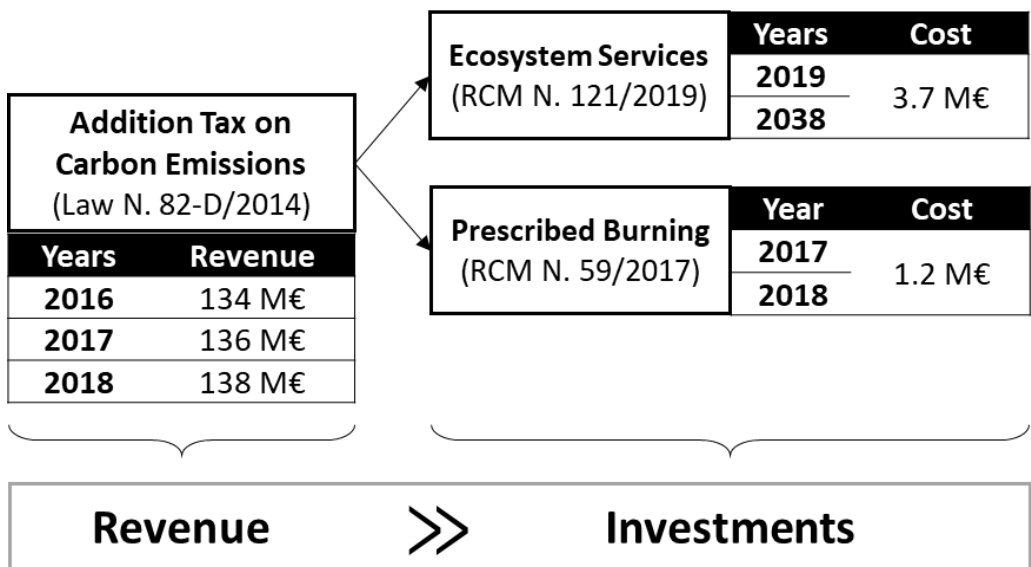


Figure 4-4 - Order of magnitude analysis. The revenue from the Addition Tax in contrast with the costs of RCM N. 59/2017 and RCM N. 121/2019.

From the gathered information for this order of magnitude analysis, despite the distinguished timeframes analyzed, it is evident that the revenue from the Addition Tax is “much greater than” the costs of the Payment for Ecosystem Services and Prescribed Burning policy combined. The revenue from the tax collected in 2016 alone is more than 25 times higher than the investments needed for the entire duration of the two policies.

By law, the revenue of the Addition Tax is directed to the Portuguese Environmental Fund. This Fund has the objective of supporting environmental policies aligned with the Sustainable Development Objectives, such as carbon sequestration, that can benefit from the implementation of the measures described in RCM N. 59/2017 and RCM N. 121/2019. Frequently ecosystem services-based solutions that can support in SDGs implementation are overlooked or underexploited [6].

Despite the viability of using a share of the revenue from the Addition Tax to fund these two policies, there are three main criticisms of financing natural climate solutions through carbon taxes, as pointed by Barbier et al. [14]. First, they can cause the shift of forest degradation to other areas. Second, they may decrease the incentive to reduce emissions via renewable energy. Third, the tax revenue should be used for different purposes. However, the authors believe that all these concerns can be addressed. A national tax scheme can reduce the probability of degradation shifts within each country. Renewable-energy production and natural climate solutions are both crucial. Lastly, despite the many worthy uses of tax revenue, the severity of climate change and biodiversity loss makes tackling both at once a priority.

This is also true in Portugal’s case. First, the tax revenues would be employed in guarding the forest and the population against extreme fire events, according to the areas’ vulnerability. Second, as the results indicated, the tax revenue far exceeds what is needed to invest in prescribed burning and biodiversity initiatives, leaving enough financial resources to be invested in renewable energies and more climate-focused actions. Lastly, climate actions and biodiversity are top concerns in the European and Portuguese environmental agenda, and therefore both should have a priority in using these funds.

Next, the individual benefits of each policy are analyzed in further detail. It is clear that the revenue from the Addition Tax is enough to support the other policies, but it is also relevant to assess if they are cost-effective.

4.3.2 *Emission factors*

The parameters commonly used to estimate emissions from vegetation fires are the amount of fuel available for burning, the fraction of fuel that is actually burned over a specific time, the area burned, and emission factors [2]. Emission factors can be presented in terms of the weight of a compound released per weight of dry fuel consumed or the weight of a compound released per burnt area, as is the case in Portugal's NIR [17]. Figure 4-5 illustrates the values of the annual average emission factors per hectare from 1990 until 2018, determined based on NIR data [17]. The numbers varied between 11 – 28 Mg/ha, having a mean of 20 Mg/ha (dashed line).

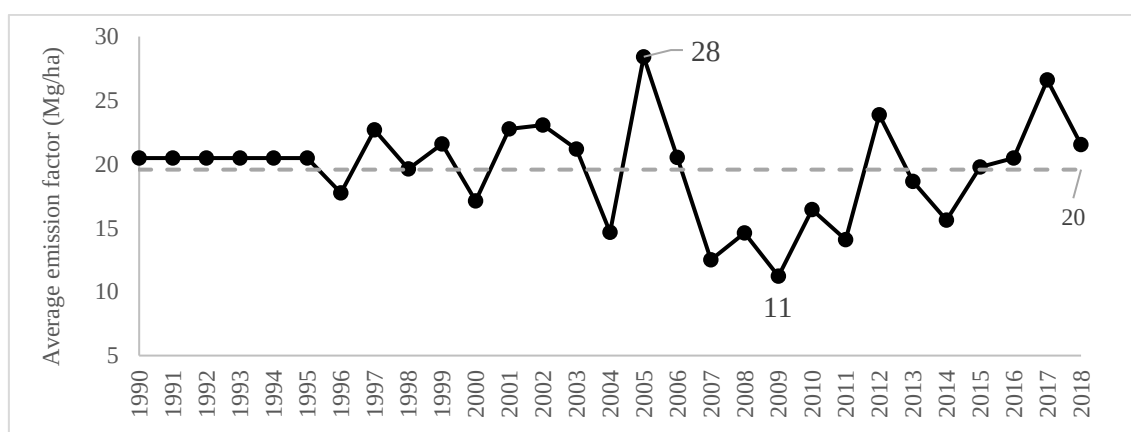


Figure 4-5 - The annual average CO₂ equivalents emission factors from 1990 to 2018. The dashed line symbolizes the mean value of the annual average emission factor (20 Mg/ha). Developed based on data from PEA (2020).

The estimations of the Emissions from Biomass Burning (CRF 4(V)) were first included in the Portuguese National Inventory Report of 2016, and the values for the years before that were determined retroactively, which led to some of them to be equal, according to data availability. The variations in these values throughout time are largely due to differences in each year's fuel and fire characteristics. To determine the pyrogenic emissions, most studies depend on the information on above-ground biomass available for burning, combustion factors, burning area, and emission factors for a certain species and vegetation type. These variables are difficult to estimate, which produces significant uncertainties in the results [26]. Even so, as indicated in Table 4-3, these values are in a range that is not too far off to what was defined in other studies that estimated the emission factors for Portugal, using different input data and methods.

Table 4-3 - Emission factors for Portugal estimated in other studies.

Values (Mg/ha)	Reference
13 - 18	[26]
40	[1]
12	[2]

For the following analyses, the extreme values of the emissions factors presented in the NIR were used to show the full range of possible monetary values for the carbon sequestration services provided by avoiding forest fires. The mean emissions factor value was included in the calculations to represent the expected (most likely) monetary figure of the carbon sequestration service.

4.3.3 Monetary value of the carbon sequestration service

Wildfires and their emissions directly affect carbon cycles by increasing the atmospheric carbon dioxide and altering carbon sequestration by terrestrial ecosystems [2]. The need to stabilize the atmosphere's carbon content has been established in agreements and policies, such as the Kyoto Protocol and the EU climate policy. Their focus is on reducing carbon emissions, but the carbon content in the atmosphere can also be offset by carbon sink enhancement. More recently, the need to act against forests' carbon releases was acknowledged in the Paris Agreement [27]. In this scenario, carbon markets play a key role in providing incentives to cut carbon emissions and promote various forms of carbon sequestration. In this sense, it has been suggested that carbon taxation can be a means to fund forest conservation measures around the world [14].

In Portugal's case, the value of the Addition Tax on Carbon Emissions is defined based on the price resulting from auctions of greenhouse gas emission allowances within the European carbon market. Figure 4-6 displays the range of the monetary values that the Portuguese forest might annually offer per hectare as a result of the carbon sequestration service provided by avoiding fires as a function of the Addition Tax through the years.

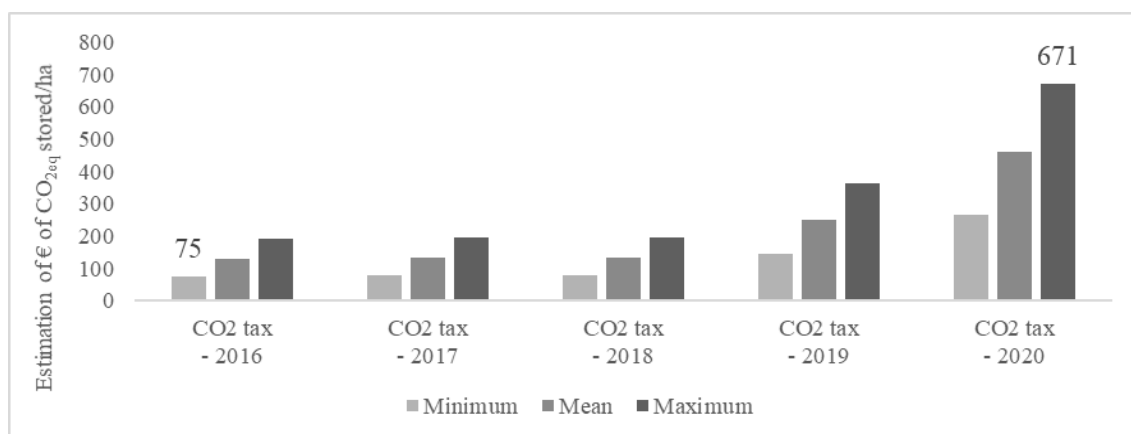


Figure 4-6 - Monetary value of CO₂ equivalents stored per hectare in the Portuguese forests.

The monetary value of the carbon that can be stored by avoiding fires varies from 75 euros per hectare in the least favorable scenario to 671 euros in the most favorable. The mean values varied from 131 euros per hectare in 2016 up to 462 euros per hectare in 2020. Since its creation, there has been an overall increasing trend in the Addition Tax figure, which led the stored carbon value also to increase. As more climate policies and carbon markets are established around the globe, it is expected that this increasing trend in the Addition Tax will continue in the future.

In the context of forests, RCM N. 121/2019 instates a new environmental policy that aims to pay for the forest's ecosystem services, which are not covered by traditional markets, such as carbon sequestration. This kind of ecosystem services-based solutions has been described as having the potential to offer co-benefits for SDGs implementation [6]. Currently, experimental projects are being conducted in two regions of the country, and the incentives paid annually for the ecosystem services provided by the forest vary between 5 and 20 euros per hectare, according to the characteristics of the forest. When comparing the range of the value of the incentives with the range of the values estimated for the carbon sequestration service, it is possible to see that higher investments on the part of the State would still have a positive return, even if only considering the carbon stored by avoiding fires. It should be emphasized that the same RCM recognizes the need to further study methodologies to best estimate the value of the incentives, and there is literature that suggests that funding forest conservation measures can be done through carbon taxation [14].

As for the savings related to forest management practices, Figure 4-7 shows the expected benefits.

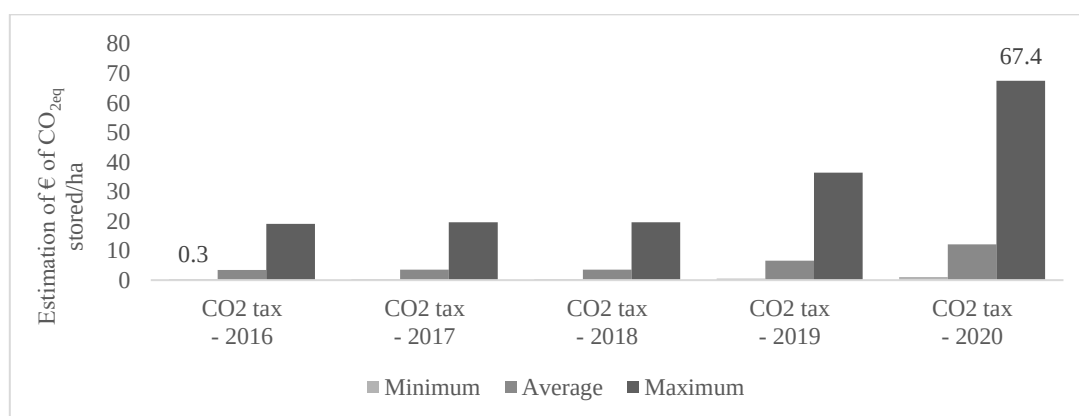


Figure 4-7 - Monetary value of CO₂ equivalents stored per hectare in the Portuguese forests, considering the effect of forest management (€/ha).

The value of the carbon that can be stored by forest management practices varies from 0.3 euros per hectare in the least favorable scenario and ascending to 67.4 euros in the most favorable. The mean values vary from 3.4 euros per hectare in 2016 up to 12.1 euros per hectare in 2020. Considering the increasing trend in the Addition Tax value, this benefit associated with management will likely rise in the future. Once more, this metric suggests that the value of the incentive provided by RCM N. 121/2019 could be revisited to further boost forest management practices.

4.3.4 Prescribed burning monetary savings

Forest carbon enhancement presents a low-cost opportunity in climate policy but needs efficient policies to be implemented [27]. Studies have shown that prescribed burning can be a valuable tool in reducing overall wildfires emissions in Mediterranean countries [1], [2] by avoiding larger fire events. In Portugal, the National Prescribed Burning Program, approved by the RCM N. 59/2017, is the primary fire prevention policy, and it is part of the National Plan for the Defense of the Forest Against Fires.

This policy acknowledges that it is vital to increase the area of active management to achieve an effective defense against fires. This is to be done by creating strips and mosaics with low fuel load strategically located to support firefighting [28]. In this sense, prescribed burning is an appealing fuel treatment alternative, as it seeks to moderate wildfire impacts and decreases the areal extent of the events by improving the effectiveness of fire suppression [29].

The monetary savings in terms of avoided CO₂ emissions per each prescribed burning treated hectare were calculated for the four scenarios proposed by Vilén and Fernandes (2011) and are shown in Figure 4-8.

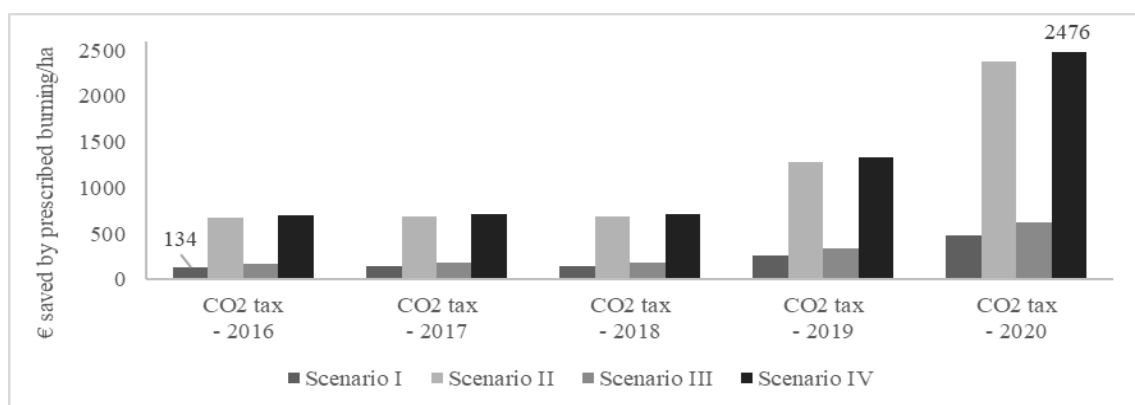


Figure 4-8 - Annual monetary savings associated with prescribed burning interventions, according to the Addition Tax and the scenarios proposed by Vilén and Fernandes (2011).

The value of the savings associated with the treatment varied from 134 euros, in the least favorable scenario, up to 2476 euros, in the most favorable. As the burn leverage used in both Scenarios I and III was of 1 ha decrease in the area burned by wildfire for each treated ha, and for Scenarios II and IV was of 3 ha decrease in the area burned by wildfire for each treated ha, their results were somewhat similar. Even so, Scenarios III and IV showed slightly better results, suggesting that interventions on larger areas (20% of the annually burned area, instead of 2%) are economically more interesting.

The Portuguese National Prescribed Burning Plan, part of the National Prescribed Burning Program, estimates that the cost to treat one hectare of land is 120 euros. Considering this information, prescribed burning measures are not only an attractive option for emission reductions (Narayan et al., 2007; Vilén and Fernandes, 2011) but also in economic terms since the value of the carbon savings surpasses the treatment investments.

It is true that uncertainties related to fire emission estimates are large and more data on fuel load and fuel consumption in different fuel layers are needed [1]. However, even considering the $\pm 58\%$ uncertainty reported, Scenarios II and IV pay off economically for all Addition Tax values to date. However, only for the Addition Tax value of 2020, all scenarios pay off, which is encouraging as the Carbon Addition Tax for 2021 has been set to 23.921 euros per Mg of CO₂ (Ordinance N. 277/2020), slightly higher than the previous year, continuing the increasing value trend.

4.4 Conclusions

Forests are regarded as the most efficient carbon sequestration systems among the terrestrial ecosystems, as the many public services they provide contribute greatly to reduce CO₂ in the atmosphere [4]. In this sense, the Portuguese forest provides various ecosystem services and goods that are valued by traditional markets, such as timber and cork. However, essential services provided by the forest, such as carbon sequestration, are not valued by traditional economies.

The first part of this study, the order of magnitude analysis, provided an initial assessment of the economic viability of using the revenue from the Addition Tax on Carbon Emissions for funding wildfire prevention and biodiversity policies, both in alignment with climate change prevention and mitigation. The results indicate that the tax

revenue is “much greater than” what is needed for investing in wildfire prevention and biodiversity conservation through the established policies. From an environmental perspective, there is clear evidence of the potential benefits of all these policies and that they can work synergistically since they all have positive impacts in mitigating climate change.

Regardless of the intrinsic uncertainties typical of policies that target carbon sequestration [27], the results have shown that prescribed burning is an interesting policy not only from a carbon sequestration perspective, as it also pays off financially. The value of the carbon potentially sequestered by prescribed burning exceeds the treatment costs for the analyzed scenarios almost always. As the Addition Tax value has been showing an increasing trend, this suggests that this benefit is likely sustainable through time.

Despite the need to jointly tackle climate change and biodiversity loss [14], it is recognized that payments for carbon sequestration alone are not likely to induce private landowners to switch to habitat restoration from agricultural activities [18], [30]. In this sense, the results of this work have shown that the value of the carbon sequestration service provided per hectare by avoiding forest fires far exceeds the value of the incentive provided by the Ecosystem Services Payment Program in Rural Spaces (RCM 121/2019) policy. If this policy is to effectively promote the restoration of ecosystems, more sustainable agricultural practices, and fire resilience, it would be economically and environmentally sensible to review the values of these incentives to make them more attractive to landowners.

Finally, there is evidence of benefits in coupling policies that can implement SDGs strategies while adopting ecosystem services-based solutions in different regions of the world [6], including Portugal, as demonstrated in this study. The successful implementation of the SDGs agenda and related local policies is necessary to address the global sustainability challenges of safeguarding human well-being, economic prosperity, and environmental protection. In this sense, the SDGs need to interact as a synergistic reinforcement system [31]. Given that combating climate change and protecting biodiversity are global priorities, explicitly addressed by the United Nations, European Union policies, other countries, especially in the Mediterranean basin, can benefit from the analysis performed and results of this study as the integration of environmental policies can potentially make them more effective, and economically viable, allowing positive synergies to occur.

4.5 References

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5 Conclusions

This thesis employed different research methods to characterize the state of the art and state of practice of wildfire management in mediterranean-climate regions, narrowing the study's focus to Portugal, which is considered a characteristic representative of the Mediterranean region for forest-management interventions. Figure 5-1 shows a summary of the structure of the thesis and its main findings.

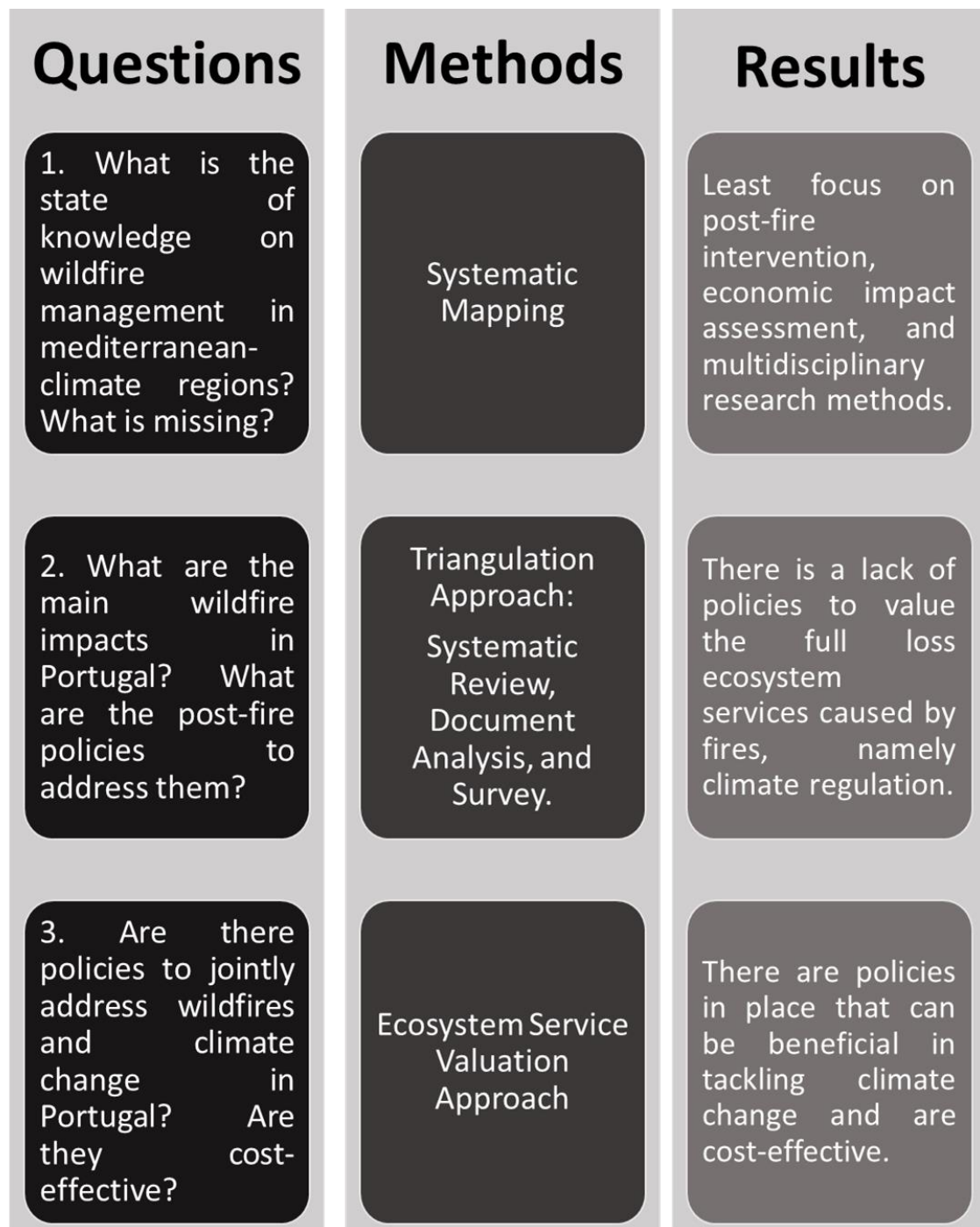


Figure 5-1 - Summary of the structure and findings of this thesis.

The final considerations regarding the results of this thesis are now presented in terms of its Empirical Findings, Theoretical Contributions, Policy Implications, and Limitations and Future Work.

5.1 Empirical Findings

The conclusions of the first stage of this study provided an overview of the current state of knowledge in the field of wildfire management in mediterranean-climate regions. It became evident that there is a significant geographic gap in the studies across all regions, and European studies, especially those conducted in characteristic representatives of the region, may serve as a reference for other continents. This stage of the work also revealed that there has been limited research with a multidisciplinary focus and using methods to incorporate expert and practitioner knowledge, which ultimately could help shape integrated management schemes. Also, it was found that very few studies focused on emergency response or assessing the social, environmental, and economic losses linked to the fires.

The second stage of this work was based on the results of the previous step. A multimethod approach was employed to understand which are the main ecosystem services impacted by wildfires. This stage was designed to incorporate scientific and expert knowledge through a triangulation approach, in which information was gathered from the literature, governmental reports, and fire management experts. The main findings of this part of the study are that a vast number of impacts to ecosystem services associated with forest fires have been studied, but not in the same level of detail. Also, more efforts could be made to valuate the ecosystem services lost due to the wildfires to better assess its environmental, social, and economic impacts and better design policies to address them.

To close this thesis, it was decided to study the possible synergies and economic benefits of policies linked to climate change, biodiversity, and fire management in Portugal. This stage of the study revealed that the policies in place, namely Law N. 82-D/2014 (Addition Tax on Carbon Emissions), RCM N. 121/2019 (Payment for Ecosystem Services), and RCM N. 59/2017 (National Prescribed Burning Program), can work mutualistically. These policies address the major concerns of most sustainable development agendas, including the United Nations and European Union, namely in terms of climate change and biodiversity loss.

To conclude, this work contributed by characterizing the state of knowledge in terms of fire management in mediterranean-climate regions, by describing the ecosystem services impacted by wildfires, and by analyzing the policies to deal with both from a mitigation perspective as well as economically through a payment for ecosystem services scheme lens.

5.2 Theoretical Contributions

The first stage of this work, in which information from all mediterranean-climate regions was gathered, contributed to theory by synthesizing previous work and identifying knowledge gaps to help direct future work in wildfire management. In fact, this stage guided the next steps in the present work and has the potential to guide further studies.

The contribution of the second stage is linked mainly to the characterization of the wildfire impacts on forests ecosystem services. In the first stage of this thesis, the lack of studies that employed multidisciplinary methods and that incorporated expert knowledge in wildfire management studies was identified. For this reason, the multidisciplinary approach employed gathered information from three different sources (scientific literature, governmental reports, and expert knowledge) and identified the main wildfire impacts that need to be further studied and managed. Impacts on the flora are well studied and addressed by policies in Portugal. However, pressing topics such as climate change are not accounted for by ICNF, neither the loss of the climate regulation service by the literature. Finally, the experts expressed that all 22 TEEB ecosystem services are impacted by wildfires, while most have not been addressed by the literature or covered by specific policies, especially regulating services. These identified knowledge gaps can serve as the basis for future research, both in Portugal and other mediterranean-climate regions of the world.

Finally, the third stage of this work aimed to help fill the knowledge gap identified in the previous stage regarding the loss of the climate regulation service linked to wildfires. This was done through a carbon sequestration perspective. In this stage, a policy analysis framework was created to consider the cost-effectiveness of individual policies, as well as possible synergistic policy interactions through an ecosystem services lens. Similar analysis frameworks can be employed in the assessment of environmental policies in other countries of the world, especially in mediterranean-climate regions.

5.3 Policy Implications

In the first stage of the research, the information gathered might be valuable for managers and policymakers as it identified relevant studies addressing various management issues and, consequently, it spares them the effort of carrying out a search fully from the beginning. Specifically, countries in mediterranean-climate regions with fewer studies, such as South America and South Africa, can benefit from this study to better structure the foundations of future research and wildfire management policies. Also, this study supports the necessity to further invest in research policies related to wildfire impacts, which still need to be addressed through a multidisciplinary perspective.

The following stage of the work identified that Portugal currently has a government agency clearly assigned to deal with forest fire impacts and a sound legal framework to instruct emergency actions. Also, the wildfires experts expressed that all the 22 TEEB ecosystem services are significantly impacted both in the short and long term and that there are not enough policy instruments to address them. ICNF appears to focus more on the services that require rapid actions to be mitigated in the short-term to avoid the escalation of the damages. However, tools that help them tackle services such as climate regulation could be particularly useful in possibly helping to avoid or reduce wildfire incidence and intensity in the first place. In this sense, this stage of the thesis contributed by indicating knowledge gaps and opportunities for cooperation between the academic community and practitioners to improve and support environmental protection programs and policies in Portugal. Moreover, this was one of the few studies to incorporate expert knowledge in its scope, which can be valuable in elaborating policies that are more urgently needed to better structure and qualify wildfire management practices as a whole.

In the third and last stage of this thesis, the policy analysis framework proposed demonstrated that these policies are not only beneficial for the environment as they are also cost-effective and can work synergistically. This type of policy arrangement is considered fundamental in implementing the UN Sustainable Development Goals, to which Portugal has subscribed. Having interconnect policies that have similar goals, such as tackling wildfire impacts and their causes, and that are economically sustainable increases their overall chances of success and tends to optimize its mutual benefits. In this sense, the approach employed here could be used to analyze other environmental policies

in Portugal, and even in other mediterranean-climate nations, serving as a sound rationale to push legislation that is cost-effective and can work synergistically.

5.4 Limitations and Future Work

The main limitations of this study are linked to the geographical scope, the breadth, and multidisciplinary of the topic of wildfire management.

This study was first restricted to wildfires in mediterranean-climate regions since these regions are fire-prone and are often studied together, as they have for long provided classic cases for comparative ecological function studies. However, especially due to climate change, other types of ecosystems, such as boreal forest, are also experiencing an increase in fire occurrence and need to be further studied. The method employed in this stage of the work, systematic mapping, provided an interesting overview of the subject, but specific topics such as preventive land and ecosystem management; fuels; fire behavior, risk modeling, and post-fire management could be studied in greater detail using systematic reviews.

In terms of the breadth of the topic, to allow studies to be conducted more in-depth, the focus was restricted to environmental impacts and policies in Portugal. This was done to better characterize the specificities of the country, which is considered a characteristic representative of the Mediterranean region. Still, the impacts of wildfire occurrences are very broad, involving environmental aspects and social and economic dimensions that were not meaningfully addressed by this thesis.

Finally, to attempt to address the multidisciplinary of the topic, multiple research methods were employed to reflect the various perspectives on managing wildfire environmental impacts. This effort yielded findings that converged to the fact that more policy is needed in key areas, such as an integrated approach to climate change and climate regulation. However, given the complexity and multiple dimensions of the wildfire issue, especially in the context of climate change, this topic still needs to be further studied in all its facets.

Some suggestions for future work that could address specific limitations of the present study are the following:

- Perform systematic reviews of specific wildfire management topics, such as: preventive land and ecosystem management; fuels; fire behavior and risk modeling, and post-fire management.

- Employ other methods to value the carbon sequestration service provided by the forests.
- Assess the cost-effectiveness of other possible fuel treatment options available, such as mechanical thinning and grazing, regarding their carbon storage potential.
- Study and value all the other ecosystem services provided by the forests that are impacted by the fires.
- Develop other studies to jointly analyze environmental policies and their synergies in terms of wildfire management, both in Portugal and other countries.

Appendix A

List of selected studies

Search string: *fire AND (“mediterranean-climate” OR “mediterranean environ*” OR “mediterranean region” OR “mediterranean eco*” OR “mediterranean forest”) AND (manag* OR polic*).

Data bases: Elsevier’s Scopus (*title*, *abstract*, and *keyword* fields) and Thomson Reuter’s Web of Science (*title* and *topic* fields).

Date of search: February 19th, 2019.

Link for full systematic map:

<https://drive.google.com/file/d/1XX4gwFnAG90zVPRgIWRudN1Jy1il9bGl/view?usp=sharing>

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Appendix B

List of selected studies

Search string: *fire; Portugal; impact* assess*.

Data bases: Elsevier's Scopus (*title*, *abstract*, and *keyword* fields) and Thomson Reuter's Web of Science (*title* and *topic* fields).

Date of search: February 2nd, 2020.

Link for full supporting information: <https://drive.google.com/file/d/1-I6IluzTeEuyOoMVbTV6maQYZsLpFQru/view?usp=sharing>

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