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Luca Salvati *Editors*

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Introduction: FIRElinks, a Community for Society and Science

Jesús Rodrigo-Comino, Artemi Cerdà, Stefan Doerr, Saskia D. Keesstra, Andrés Caballero-Calvo, Rita Sobczyk, and Luca Salvati

Abstract **FIRE*links* *(CA18135)*** originated from many efforts by a group of researchers after submitting a proposal for a COST Action. During four years, the main aim has been to develop an EU-spanning network of scientists and practitioners involved in forest fire research and land management with backgrounds such as fire dynamics, fire risk management, fire effects on vegetation, fauna, soil and water, and socioeconomic, historical, geographical, political perception, and land management approaches. Communities from different scientific and geographic backgrounds allowing the discussion of different experiences and the emergence of new approaches to fire research were connected. Working group number 5 was developed to power synergistic collaborations between European research groups and stakeholders to synthesize the existing knowledge and expertise and to define a concerted research agenda which promotes an integrated approach to create fire-resilient landscapes from a regional and socioeconomic point of view, taking into account how to teach the population, stakeholders, and policymakers considering the

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biological, biochemical, and physical, but also socioeconomic, historical, geographical, sociological, perception, and policy constraints. In this edited book, the main conclusion of working group 5 was addressed considering different study cases and methods developed by recognized experts over Europe: there is an urgent societal need to manage wildfires due to the expected further intensification and geographical spreading of its regimes under global change.

Keywords Wildfires · Vegetation · Risk · Socioeconomic background · Drivers · Europe · Globalization · Climate change

1 Fire in the Earth System. Since the Beginning with Us

Fire has been part of the Earth System for the last 400 million years, and humans are the sole species that controls and manages fire. We have used fire for over a million years, both as hunter-gatherers managing the landscape with fire and as farmers using fire as a low-cost, efficient, and ecological tool for clearing and maintaining the productivity of the land. Fire has been highlighted as the most influential element in the development of human societies (Allen et al., 2002). The increase in prolonged dry and hot periods observed in many regions of the world is exacerbating the risk of fire (Vegas-Vilarrúbia et al., 2011). The causes of increased fire risk are not only linked to climate change but are also a consequence of economic and social changes and political decisions (Salvati & Ferrara, 2015). Over the past few decades, many countries' rural areas have seen significant depopulation and a reduction in land management as residents moved to cities or even other countries in search of work. The resulting rural depopulation has led to revegetation of the abandoned agricultural land, which favors fire spread (Kabadayı et al., 2022; Zhang et al., 2022). The landscape once dominated by farming, grazing, and open forest land has been replaced with denser vegetation such as plantations of pines and eucalyptus or naturally reforested areas in the earlier stage of vegetation succession. This switch has created an ecological system with high flammability (McColl-Gausden & Penman, 2019; Ormeño et al., 2020).

This abandonment of farmland has resulted in an expansion of the forest, shrubs, and grassland and has led to a more connected landscape in Europe. Therefore, the risks related to fires in forests, grasslands, and shrublands are expected to increase due to four key factors: (i) the expansion of forests due to land abandonment and afforestation; (ii) the increase in fuel load and fuel continuity due to reduced land management; (iii) greater ignition potential due to population growth in the urban/rural interface; (iv) climate change induced higher temperatures, increased wind speeds, and increased probability of prolonged dry periods promoting vegetation flammability; and (v) the growth of the urban areas closer to forest land.

The enhanced risk of fires is moving beyond the capacity of even the best-funded wildland fire fighting teams and therefore calls for the development of new approaches to fire management (Moreira et al., 2020). Instead of focusing primarily on increasing firefighting capabilities, a more effective approach is needed that focuses on long-term fire prevention through vegetation management by reducing fuel load or managing fuel type and fuel continuity at a landscape level or using new technologies (Alsharif et al., 2020). In addition, it needs to be accepted that fire plays an integral natural role in some ecosystems. Therefore, we need to create fire-resilient landscapes, which can host sustainable fire regimes (McWethy et al., 2019). This calls for the construction of a new relationship with fire that balances ecosystem, societal, and long-term Earth System requirements. To be able to develop and implement such a novel strategy effectively, many questions need to be answered both from a scientific and from a policy, perception, and socioeconomic point of view.

Understanding fire and its impacts requires research integrating the engineering, physical, biological, chemical, and social sciences, to address the array of relevant aspects such as fire risk, prevention, behavior, suppression, fire effects on vegetation, and soils as well as biogeochemical and geomorphological processes, but also socioeconomic factors and the ecosystems services they provide. However, even though these aspects of fire are all interlinked, they are typically researched in isolation by the different scientific disciplines, often neglecting their common wider issues that need to be clarified to enable the effective development and implementation of coherent management strategies and policies. There is insufficient communication across the fire science community, which is one of the most diverse of all scientific communities and embedded within different scientific disciplines, from risk management and social sciences to ecology, soil science, and hydrology (Errett et al., 2019; Fisher et al., 2020; Humphrey et al., 2021). The limited exchange of knowledge and data between these fire research teams has hampered the overall advance of understanding in managing the fire. We identify several major communities of researchers: (i) firefighting; (ii) vegetation ecology; (iii) soil-hydrology-erosion; (iv) socioeconomic-policy-perception; (v) fire understanding and modeling; (vi) fauna; (vii) C-sequestration and soil organic matter quality; and (viii) historical and geographical approaches.

"FIRE*links*", a funded COST Action (CA18135) from 2019 to 2023, aimed to achieve this goal by accelerating cross-disciplinary communication between fire scientists, with the overall goal to provide policymakers and land users with strong, research-lead foundations that enable the implementation of more effective land management approaches. The working group members and Management Committee during the last four years concluded that only holistic landscape management will provide a sustainable solution to the accelerating problem of fires and is essential to achieving sustainable fire management (Fernandez-Anez et al., 2021).

Wildfires are a common occurrence every summer, and the risk of devastating fires does not only affect the southern EU countries. Fire also affects Alpine (Müller et al., 2020), Temperate (Kolanek et al., 2021), Boreal (Venäläinen et al., 2020), and Tundra ecosystems (Masrur et al., 2022), with particularly notable 2010 fires around Moscow, which led to many smoke-related deaths (Nefedova, 2021), the 2014 fires in Sweden (Pimentel & Arheimer, 2021), their largest in recorded history, and even large fires occurring in Greenland (2017) (Evangeliou et al., 2019). Climate change is increasing the risk of such extreme fires, exacerbated in some regions by rural land abandonment, and increased ignition probability in the growing rural/urban interface (Mansoor et al., 2022). Increased fire risk highlights the need for research in several critical areas of science, for example, how fire spreads in these complex ‘fuels’ and how this spreading can be prevented, how to respond to fire emergencies, and how humans behave during emergencies. Equally important is the understanding of the processes occurring after a fire in terms of the changes to vegetation dynamics, soils, and water, considering different scales (Rodrigo-Comino et al., 2018, 2020). In this context, the effectiveness of post-fire rehabilitation treatments on water and sediment dynamics is highly relevant here. However, this scientific knowledge needs to be further developed and transformed into usable knowledge and tools for practitioners to create effective post-fire management strategies.

In this book, we tried to collect some experiences coming from FIRElinks and working group number 5 under a regional geographical and socioeconomic perspective. In this book, all the chapters pretend to show the efforts and tools used to improve a strong communication network with stakeholders to allow all research needs to emerge. Without a better understanding of fire and management processes including novel technologies needed to protect goods and inhabitants, it is clear that we cannot provide a safer environment to worldwide citizens. There are limited opportunities for sustained and concerted scientific discovery or coordination of efforts among EU research institutions working on the fire. Many of which are world-leading in this field, but disconnected from each other.

2 Main Goals and Challenges to Be Achieved from Now in Fire Research

After starting FIRElinks, some objectives were planned related to the main challenges that forest fires are generating nowadays. In this sub-chapter, we present the main ones when this COST Action was started and this book finished. The rationale of these goals is divided into two different groups. The former one is related to research coordination and can include 10 objectives:

1. Bridging research and communication gaps between different fire researches communities.
2. Coordination of information seeking, identification, collection, and/or data treatment.
3. Synthesizing the existing knowledge and data to determine an integrated state-of-the-art.
4. Standardization and integration of experiments, measurements, monitoring, and interventions.
5. Assessment of models that focus on fire risk, fire behavior, and fire-induced landscape changes.
6. Exchanging of know-how on fire prevention, firefighting, and post-fire restoration.

7. Involving stakeholders in defining the needs for fire research and coordination of actions.
8. Pan-European web-based database for practitioners, with management strategies/effectiveness and develop a web-based scientific collaboration network.
9. Establishing an annual European conference on integrated fire research, a European Society of Fire Research and Management and exploit a plan through demonstration and dissemination: technical reports/brochures/media.
10. Bringing a wholesome picture in understanding fire dynamics, risks, and management strategies.

The latter one is related to the possible capacity-building goals extremely joined with the current societal challenges highlighted by international institutions:

1. Harnessing the experience and expertise in the field of fire research across diverse environments to bring together groups of scientists and practitioners working on different aspects.
2. Moving forward from studies focusing on specific aspects of the impact of fire on the Earth System to a holistic approach that will underpin effective management strategies.
3. Streamlining and harmonizing current research methodologies to assess fire dynamics and fire effect.
4. Promoting discussions and cooperation among researchers and practitioners who are the basis for new research, through the cross-fertilization of ideas and approaches from various fire research disciplines.
5. Encouraging and facilitating collaboration between scientists and land users, allowing practitioners and policymakers to benefit, which is a crucial facet for implementation management tools.
6. Increasing awareness of the fire issues and attract others to be involved and participate in forest fire disciplines such as Early Career Investigators (ECIs) and practitioners and scientists from inclusiveness countries or from areas with recent issues of forest fires.
7. Transferring to the society key and basic information about the role of fire and its sustainable and safe management in the Earth System in the twenty-first century.

3 Progress Beyond the State-of-the-Art and Innovation Potential in Europe

Fire is widespread in many regions due to the extensive land abandonment in the late twentieth century that led to increased frequency and severity of wildfire risk (Mantero et al., 2020). This has increased the risk of human and economic losses, changes in vegetation cover, surface runoff, and soil degradation and contamination of the water bodies of streams and reservoirs with toxic compounds in ashes. Fire is a natural phenomenon that affects Earth's ecosystems and needs better research networking to face the challenges of scientific development and landscape management. In this book, we highlight that Europe needs to take advantage of the knowledge developed by scientists and practitioners. Fire dynamics and behavior are essential to understand fire prevention and predicting the environmental impacts of fires (Carlucci et al., 2019). Building an understanding of the types of fire behavior (energy release, spread rates, and conditions of extinction) that occur in our changing landscapes such as abandoned agricultural sites and across newly connected ecosystems is essential if we are to effectively manage fire prevention and emergency responses to fires in these areas (Meira Castro et al., 2020). Moreover, under climatic change and shifting biogeographic vegetation patterns, novel fire behavior begins to affect regions that have not previously had a significant fire history or fire management infrastructure.

Therefore, an understanding of fire dynamics in Europe's climate and ecosystems is required as well as coupled research on emergency response (onsite and offsite) and monitoring, mapping, and adoption of new firefighting strategies and decision-making strategies to manage, prevent, combat, and fight forest fires that might display a range of fire behaviors (Monedero et al., 2019; Wunder et al., 2021). Post-fire management strategies need to consider fire severity and the interplay between fire dynamics and behavior, fire severity, and the long-term effects on ecosystems following extreme fire events. Key research on these topics has been undertaken in Europe by different research teams, and an understanding of fire behavior under field and laboratory conditions has evolved. While fire will remain a recurring phenomenon in many regions, prevention of extreme fires is necessary to reduce risk to humans and infrastructure and to achieve sustainable management of the land and resources. Here, linking the different research teams working on understanding fire behavior and fire prevention in Europe is essential to promote better science and management. In particular one of the recent advances in Europe is the discussion of innovative fire prevention strategies such as the use of low-intensity prescribed fires (Espinosa et al., 2021; Petersson et al., 2020). In Europe, there is a need to improve prescribed fire management and, more critically, public acceptance as a strategy for future land management (Francos & Úbeda, 2021).

3.1 Biota and Fire Are Twins

Fire can generate mosaics where different species, with different optima, can coexist, allowing some fire regimes to enhance biodiversity, while other fire regimes pose a threat to biodiversity (Pausas & Ribeiro, 2013). Plants provide the fuel for the fire to burn, and the behavior of fires feeds back to determining ecosystem composition. All plants are affected immediately by fire, but many plants are adapted to fire and may even require fire for reproduction. One fire adaptive strategy is the highly resilient pine cones that only release seeds following heating by a fire; specifically, it is stimulated via the smoke which induces flowering and germination. The research related to the evolution of plant cover and species in response to forest fires is relatively well developed, but it needs synthesis between different ecosystems to establish general rules and learn from findings found in different regions with different fire recurrences (Fernández-Raga et al., 2021). Critically, we need to consider how such adaptations will fare against changing fire behaviors and biogeographic shifts (Stevens et al., 2019, 2020). As such it is necessary to move from local- and regional-scale measurements to global interactions, potentially over macro-evolutionary timescales (Pausas et al., 2009). This is essential to build an understanding of the interaction with climate change. In terms of faunal changes, the biological changes induced by fire have been mainly researched at the microfaunal scale (Santos et al., 2019). As such, there is a lack of investigation into the impacts on macrofauna (Hakim et al., 2019). The effect of fire on fauna and plant-animal interactions is still poorly known. The findings on biota research show that fire is a key element in Earth System evolution, and we must find a solution to cohabit human societies and fire.

3.2 Fire and Soils

Fire affects soils and landforms due to the heat pulse delivered by a passing fireline (Bento-Gonçalves et al., 2012). Changes in the physicochemical properties of the soil occur, but these are also a consequence of vegetation cover and soil erosion (Cerdà et al., 2017). Previous research has mainly considered fire effects on soil organic matter, aggregate stability infiltration, and associated soil properties. However, it has also been shown that the soil needs decades to recover after a fire event, and these longer-term effects on soil properties have received little scientific attention. Moreover, C-loss and C-sequestration in soils following fires have only in a few cases been quantified (Campo et al., 2008). Despite this, the role fire plays in the change in the soil system in terms of soil properties and functions and associated ecosystem services needs further attention in science.

3.3 Water Cycle and Fire

Fire effects on runoff, sediment, and pollutants delivery are a consequence of several vegetation and soil changes which increase post-fire runoff discharges and soil losses, including ash and associated contaminants, which can negate ecosystem services such as the regulation of floods and water quality (Cerdà & Doerr, 2008). The duration of the increase in soil erosion is called the "window of disturbance" and can be short (two years) or long (decades), depending upon the vegetation recovery and the rainfall characteristics after the fire. The associated substances such as solutes, sediments, sediment-bound pollutants as well as ashes themselves find their way to waterways and reservoirs where they cause problems for ecosystems and water quality. There is a large body of literature based on research conducted at small scales (plots and hillslopes); however, studying the relationship between fires and downstream effects has been hampered by a lack of catchment-scale data for burnt areas capable of highlighting long-term erosion rates, hydrological connectivity, and sediment transport pathways, as well as due to a limited understanding of connectivity itself and how it is impacted by the fire (Hosseini et al., 2016; Malvar et al., 2016). There is also a lack of data on post-fire contaminants in streams and especially in water bodies which serve as domestic water sources. Little attention has been given to the long-term effects of fire, especially on the impacts of the recurrence time and multiple fire events on hydrological fluxes and the amount of sediment, solutes, and associated pollutants. Modeling could provide a tool to overcome these data limitations. Finally, post-fire effects can be addressed through post-fire solutions to reduce soil and water losses after forest fires, such as mulches to reduce the delivery of material and construction of erosion barriers along the contours of slopes.

3.4 Fire Implies Risks

Risk for human beings and economic investment. There is a large research background on risk assessment and risk management due to fire. Fuel mapping has been a key tool to assess fire risk. The management of the risk has been partially solved with thinning and fire extinction, but eliminating fire ultimately increases future fire risk due to the unhindered biomass accumulation and its spatial continuity in the forest, shrubland, or grasslands (Colantoni et al., 2020; Errett et al., 2019). This is why prescribed burning is now being seen as the most promising and sustainable fire management tool in many regions. The US and Australia have been pioneers, but many European regions will need to undertake additional research on this topic to achieve sustainable management. The risks associated with fire go beyond the duration (i.e., day(s) burnt) of the fire itself. After the fire, the risk of soil erosion and flooding increases, as well as the risk of pollution by the ashes. Air pollution is also a key issue such as the vast smoke hazes experienced in Indonesia via peat smoldering for oil palm plantations were found. This requires atmospheric and health scientists to join the fire research community. Effective management of fire-affected land is strongly dependent on the perception of stakeholders (Górriz-Mifsud et al., 2019). Fire is a result of a complex interaction between natural and human systems including afforestation activities and agricultural land abandonment. A key component of risk reduction is the effective management of vegetation fuels, which can be achieved effectively if stakeholders understand the benefits of vegetation management (Bowman et al., 2020). Current thinking takes this idea further, proposing management of the territory by the local population under an improved legal frame that will reconsider some of the thinking that lies at the root of the modern forest fire problems. This is a key topic that has seen little research overall and is in a limited way linked to the socioeconomic work that has been carried out on fire risk. There is a need to understand the sociology of the communities affected by forest fires and their perception. The contribution of the geographical approach to fire research and management is also relevant to the progress of the disciplines.

3.5 Innovation in Tackling the Challenge

Future innovations should be the creation of links between the existing groups of scientists working in very different fire research domains—fire regimes, fire behavior, post-fire impacts and socioeconomic, perception and historical–geographical issues, and to bring into the global community the researchers and stakeholders (land users, practitioners, policymakers, and citizens), who require a synthesized, applied understanding that is based on robust scientific evidence to support their decision and policymaking for effectively managing the increasing risk of vegetation fires in Europe in the next decades. The knowledge that these groups can share will facilitate a marked change in the progress to live sustainably and safely with fire in the Earth System. Connecting researchers working on different disciplines will achieve a global view of the fire effects on the Earth System. A good example of this is to promote the collaboration of the more traditional research fields such as fire effects on soils and vegetation to be linked with other fields such as the fauna and their behavior. The second innovation we conclude is to organize and synthesize existing data and to assess how research gaps may be filled with the information that is already collected. The third innovation must be the development of holistic strategies to manage fire-prone areas with the informed consensus of all actors involved: scientists, policymakers, land users, and citizens.

Underpinning these innovations is the development of a new approach to tackle fire risk in all European countries by taking land management, socioeconomic, and climatic changes into account. For this, it is necessary to not only connect scientists but also to connect scientists to all stakeholders related to vegetation fires, such as forest management authorities/owner associations, civil/fire protection agencies, water management authorities/supply companies, citizens, and local governments in fire-affected areas. By connecting to society, new long-term forest and land management strategies can be supported by science and policies. These new management strategies need to be economically viable and take into account ecosystem services. A web and social media dissemination program and a database with ecosystem management strategies and their effect on fire risk and ecosystem resilience to fire will facilitate the interaction with stakeholders. In FIRElinks, and also the conclusions obtained from working group 5 for this book, it is demonstrated that there is the necessity to include a series of stakeholder meetings that contribute to the exchange of knowledge and promotion of new ideas to achieve sustainable management of the fire-prone areas. Those meetings should be organized at least once in each of the main regions involved. Each fire-related discipline usually organizes its specific conferences, and cross-fertilization of the knowledge and data that is generated in these groups is therefore often not achieved. There is a need for a strong network of fire researchers in Europe, and this must be tackled for the first time across all relevant fields in other continents too.

In addition to the need to launch collaborations between scientists, there is the societal obligation by scientist to disseminate scientific findings to practitioners and policymakers. It is urgently required to organize meetings specifically aimed to seek guidance from practitioners for which specific questions they need scientifically robust answers. In addition, the experiences of the countries around the Mediterranean that have garnered by living in a fire-prone landscape should be shared with stakeholders from the rest of Europe and the world, where due to climate change more fires are predicted to occur. The main objective should be to provide a platform allowing scientists from different disciplines related to fire to collaborate and network with each other, with practitioners, land managers, and policymakers, capitalizing on the diverse experience of colleagues coming from different regions. The final output should be to arise solutions to the fire-prone areas based on the consensus of all the actors involved.

The current research and management fragmentation into different aspects of fire is divided not only among disciplines but also into different regions and stakeholder groups. For example, the group on fire dynamics is mainly focused on the physical behavior of the fire. This group, which is linked to fire-climate modelers, has a strong network in the USA and Europe, and they organize their conferences (e.g., Fire Summit, International Conference on Forest Fire Research, Congress on Combustion and Fire Dynamics). A second distinct group works on fire effects on soil, water, soil, and pollution of the environment and how to manage the landscape after a fire has occurred. This group also has scientific meetings (Fuegored, FESP, EGU-SSS) and consists largely of university staff with limited links to land managers and society. A third group focuses on fire risk management and suppression and is organizing independent congresses and meetings such as the Aerial Firefighting, Large Fire Management, or UK-Wildfire conferences. This group has a good connection with practitioners such as firefighters, and several NGOs are active to promote good practices in fire prevention and risk management. The experiences of the fire dynamics and risk management groups in connecting to society will be used to link all fire-related knowledge to societal bodies to transform scientific knowledge into usable tools for management. A fourth group is an ecologist-botanist working on plant-fire interaction and evolution (e.g., Association for Fire Ecology with their conference). They are the pioneers to see fire as a tool, and they highlight the key role of fire in the Earth System. And the fifth group is composed of Civil Protection specialists, and their perspective is crucial in firefighting and practicing. The EU initiatives such as the European Commission's Emergency Response Coordination Centre (ERCC) are a good example of this key group of stakeholders working on fire-related issues. The interaction of the abovementioned groups will develop new ideas to allow fire and humans to coexist in an urban post-industrialized society. The interaction and networking among scientists, stakeholders, and regions will be the key to the success.

4 What Can You Find in This Book?

After this introduction, readers can find in Part 1 "Regional management, strategies and work with stakeholders", chapters aimed to assess regional policies and societal issues that focus on fire risk, fire behavior, and fire-induced landscape changes. Moreover, we discuss a potential exchange of know-how on fire prevention, firefighting, and post-fire restoration, involving stakeholders in defining the needs for fire research and coordination of actions. Topics such as the Green Deal, the Sustainable Development Goals, and European Policies and how fire management can be part of the solution are discussed in several chapters. Also, the use of stubble burning as a cause of wildfires and farmers' motivations or education as a factor for forest fires are discussed. Then, Part 2 "Forest management as a key solution to starting" contains chapters related to making a deeper analysis focusing on how efficient management will support the society and natural ecosystems and even can be part of the indispensable solution. It will be showed study cases from forest fire risk management in Turkey, the Czech Republic, Bulgaria, or Portugal. Furthermore, in Part 3 "Economic aspects, dissemination and transference", the readers can find chapters aimed to explore and present the key steps to designing research and management plans considering economic and human perspectives. Moreover, we present how the use of new technologies and social media allows us to efficiently exploit a plan through demonstration, dissemination, technical reports, films, and press.

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Evaluation of the Use of Direct Seeding System Instead of Stubble Burning as a Main Cause of Possible Wildfire

Tugrul Yakupoglu, Turgay Dindaroglu, Osman Akarsubasi, Jesús Rodrigo-Comino, and Artemi Cerdà

Abstract In today's world, despite the advent of new technologies and advances in telecommunications to demonstrate the negative impacts of fire, wildfires continue to pose one of the most life-threatening challenges to natural and human ecosystems. Recent records confirm that forest fires can grow and lead to significant blazes during the stubble burning process practiced by farmers. In Turkey, for instance, stubble burning accounts for 184 out of 2,698 registered forest fires. Stubble burning brings with it numerous associated environmental problems. This chapter explores whether the direct seeding (DS) system, an environmentally friendly practice that supports sustainable agriculture in lieu of stubble burning, can serve as a viable alternative. The study includes various applications related to DS in Yozgat, Turkey, situated in Central Anatolia. This region is characterized by a semiarid climate that relies on rainfed agriculture. After implementing DS for three years, farmers witnessed substantial increases in yield, although these improvements may vary depending on various factors. Qualitatively, it is evident that farmer impatience plays a pivotal role in driving the adoption of DS techniques. To mitigate the risk of wildfires caused by stubble burning, there is an urgent need for more comprehensive farmer education

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programs on DS. Widespread adoption of DS could ultimately eliminate the threat posed by stubble burning-induced wildfires.

Keywords Farmers · Fire · Soil management · Soil tillage: stubble

1 Introduction

The challenges our world faces in the twenty-first century include global threats like climate change, accelerated soil degradation, desertification, and the reduction of biodiversity. All of these issues are intricately linked to water and food security for a human population projected to reach 10 billion by 2050. When analyzing the evolution of agriculture and farming, it becomes imperative to address future soil management systems in the context of these challenges (Lal et al., 2007). One of the significant threats to human life in many parts of the world is the occurrence and intensity of wildfires. These fires are becoming increasingly challenging to control due to global climate change and unsustainable land management practices that fail to control urban expansion and rural activities.

It has been demonstrated that one of the primary causes of forest fires is the practice of farmers burning stubble, which refers to the rooted stems left in the field after crop harvesting. Stubble burning has numerous adverse impacts on agriculture, the environment, the economy, and human health (Yakupoğlu et al., 2022). What initially began as an innocuous practice by farmers can result in uncontrolled forest fires due to carelessness and strong winds. Stubble fires are more likely to escalate into wildfires in dry farming areas, particularly in semiarid and arid climates.

In this book chapter, we aim to present a case study of Yozgat province, located in the heart of Turkey, in Central Anatolia, where the annual total precipitation averages 413.6 mm (1991–2020) (TSMS, 2022a, b). Rainfed grain cultivation is prevalent in the region, and it is a common practice for farmers to burn stubble after harvesting, with the majority believing it to be a traditional and acceptable practice (Gursoy, 2012). According to the 2019 data, Turkey experienced a total of 2698 forest fires, with 184 of them attributed to stubble burning (Yakupoğlu et al., 2022). As an illustrative example for our readers, the primary objective of this book chapter is to provide insights into the assessment of rural inhabitants' practices, particularly focusing on the adoption of direct seeding (DS), a conservation tillage (CT) method used to manage stubble without resorting to burning. Additionally, we aim to share knowledge gained from farmer training programs, field days, and the crop production experiences of farmers who have embraced DS in Central Anatolia.

2 Soil Tillage Systems

Before delving into the topic of direct seeding (DS), it is beneficial to provide foundational information about tillage and introduce soil tillage systems. Tillage serves as the initial stage in plant production and is defined as the process of manipulating soil particles to align with the needs of plants, accomplished using machinery or manual activities. Tillage processes encompass cutting, relief, tilting, mixing, shredding, chipping–spinning, and compaction. The primary objective of tillage is to optimize the conditions required by cultivated plants for their development, namely water, air, temperature, and nutrients, and to align them with plant preferences. Proper tillage establishes the desired physical conditions in the rhizosphere, a critical factor in maintaining soil quality and facilitating the balance and movement of air and water (Bayram et al., 2015).

It is important to note that the choice of tillage system can influence various factors that impact soil respiration, including plant residue, soil temperature, water content, pH, redox potential, microorganism species and population, and soil ecology (Kladivko, 2001; Polat, 2020). The disruption of the soil's ability to fulfill essential functions that determine its productivity is often attributed to human-induced effects, particularly tillage (Günal et al., 2015). Soil tillage systems are studied by experts in the field, typically categorized into two groups: (i) traditional tillage (TT) and (ii) conservation tillage (CT) (Aykas et al., 2005). In traditional tillage (TT), the plow serves as the primary tillage tool for seedbed preparation, with soil tilled to a depth of 25–30 cm. Secondary tillage machines are employed at later stages (Kabaş, 2022). In TT, more than 85% of crop residues are buried in the soil, leaving less than 15% on the soil surface. While TT played a pivotal role in the history of agriculture and benefited from mechanization, it is now associated with several recognized disadvantages:

(i) Soil compaction due to excessive field traffic.
(ii) Long-term transformation of lumpy/granular soil structure into a finer grain state.
(iii) Rapid depletion of soil organic matter.
(iv) Increased susceptibility to wind and water erosion.
(v) Gradual reduction in soil moisture levels, making it harder to maintain.
(vi) Potential CO_2 emissions when crop residues are burned.
(vii) Higher fuel costs, often reaching up to 8 L per day, due to elevated energy requirements.
(viii) Longer time requirements (İşler, 2020).

These disadvantages underscore the significance of exploring alternative tillage methods, such as conservation tillage (CT), to address contemporary agricultural challenges. The fundamental tillage system developed to mitigate the drawbacks of traditional tillage (TT) is conservation tillage (CT). As a general guideline, it is recommended to maintain at least 30% of the field surface covered with plant residue in CT (Köller, 2003). CT aims to achieve two primary objectives: (i) retaining preplant or post-harvest crop residues on the field surface or in layers near the surface; (ii) reducing the intensity of soil tillage (Aykas et al., 2005). CT systems, in contrast to TT, primarily involve limiting land preparation activities to shallow depths, preserving and managing crop residues, and preventing soil inversion, thereby reducing soil degradation (Cunningham et al., 2004). Various CT sub-systems exist, including non-inversion tillage, eco-tillage, minimum tillage, mulch tillage, reduced tillage, zone tillage, and direct seeding (DS) (Abdalla et al., 2013). Direct seeding (DS) is sometimes referred to as no-till, zero-tillage, or slot-plant. Alternatively, CT can be categorized into subclasses, including: (i) minimum tillage; (ii) reduced tillage; (iii) mulch tillage; (iv) strip tillage; (v) ridge tillage; and (vi) DS. These different approaches within CT provide flexibility in adapting to various agricultural and environmental conditions.

Minimum tillage is the minimum tillage of the soil that is necessary to meet the crop production and cultivation requirements in the existing soil conditions. Reduced tillage is a system consisting of processes that require less energy than traditional tillage and processes the soil less than conventional tillage. Mulch tillage is a moisture barrier soil tillage system. The basis of this tillage method is to treat the entire soil surface by leaving the plant residues especially on the soil surface or near the surface. Strip tillage is the treatment of < 30% of the soil surface in the form of tapes or strips. Ridge tillage is the system on which the plant will be planted and which creates ridges during maintenance or after harvest and protects them in the same place every year. In this system, the soil is usually left untouched from harvest to planting, except for fertilizer applications. Direct seeding (DS) is the process of sowing seeds directly into previously undisturbed soil. In this system, the soil is left intact from planting to harvest and from harvest to planting (Ozturk, 2014; Gurlek, 2015).

Numerous studies have demonstrated that conservation tillage (CT) offers several advantages over traditional tillage (TT) methods (Filipovic et al., 2006; Kasper et al., 2009; Almeida et al., 2018; Tang et al., 2019; Komissarov & Klik, 2020). These benefits can be summarized as follows:

(i) Reduced soil deformation in CT results in decreased soil moisture loss.
(ii) Undisturbed soil surfaces in CT reduce the chances of weed seed germination.
(iii) Lower soil deformation leads to reduced fuel consumption in CT.
(iv) Plant residues covering the soil surface in CT protect against wind and water erosion.
(v) The upright stubble left in the field during winter in CT prevents snow from being carried away by the wind, which is crucial for providing the necessary chilling for certain grains.

Compared to traditional plow-based tillage, it has been observed that reduced tillage (RT) and direct seeding (DS) methods contribute to increased soil organic matter, improved soil structure, enhanced durability, greater water retention in the soil, and improved biological properties (Barut et al., 2010; Pagliai et al., 2004; Xu & Mermoud, 2001). Furthermore, studies have shown that in general, reduced tillage (RT) and direct seeding (DS) can increase energy efficiency by 25–100% and reduce energy requirements by 15–50% (Yalçın et al., 2003).

These findings highlight the significant benefits of conservation tillage methods for agriculture.

In a study that investigated the impact of different tillage systems on soil and water losses in the Mediterranean climate zone under artificial precipitation (Yakupoğlu et al., 2021), the researchers observed significant differences. In the Kahramanmaras location, it was found that surface runoff and sediment yield from sainfoin and wheat plots under the reduced tillage (RT) system were lower compared to plots using the traditional tillage (TT) system. However, in plots planted with sainfoin in the Tarsus location, the study revealed that the effects of tillage systems on soil and water losses were insignificant.

In this study, the average soil loss from fallow, wheat, and sainfoin plots in the Tarsus location was recorded as 871 g/m^2, 307 g/m^2, and 93.68 g/m^2, respectively. In contrast, for plots in the Kahramanmaras location, the corresponding figures were 29.21, 11.25, and 3.45 g/m^2. These findings underscore the success of the conservation tillage (CT) system in reducing erosion, but they also highlight the influence of soil properties and plant variety on the effectiveness of this system.

3 Direct Seeding as an Alternative to Stubble Burning Which is a Regional Issue

The extensive use of plows, despite their limitations as a resource, led to the deterioration of soil structure due to over-processing. This practice also resulted in increased erosion, reduced soil water retention, and decreased organic matter content due to the intensity of processing. In response to these drawbacks, efforts to develop alternative tillage methods began. Notably, the inclusion of certain herbicides marked a significant milestone in this development process, eventually paving the way for the adoption of direct seeding (DS) into agricultural management in the early 1960s.

Subsequently, with the development and mass production of suitable crop residues for stubble cover, DS gained popularity in the cultivation of second-crop soybeans and corn in the United States, Brazil, Argentina, and England toward the end of the 1960s (Gözübüyük et al., 2012).

The advantages of DS are manifold:

(i) It reduces the risk of erosion.
(ii) DS increases soil infiltration and reduces evaporation, enabling better water retention in the soil.
(iii) The practice improves soil structure by increasing the organic matter content in the topsoil.
(iv) DS promotes biological activity in the soil.
(v) It reduces the need for multiple machinery, tractor power requirements, fuel consumption, and maintenance costs for mechanization.
(vi) DS enhances efficiency, especially in regions with limited humidity.
(vii) It increases available water content.

(viii) DS is well suited for application in light- and medium-textured soils, well-drained soils, volcanic soils, and moist–semi-humid regions.
(ix) It saves time in the planting process.
(x) DS helps regulate temperature around the seeds.
(xi) It reduces field traffic, crucial for mitigating soil compaction, and offers advantages in time-sensitive situations.
(xii) DS reduces greenhouse gas emissions, particularly CO_2.
(xiii) It reduces the preparation time needed for planting, decreasing dependence on weather conditions at planting dates.
(xiv) DS prevents the formation of a soil crust that can impede plant emergence and cause runoff (İşler, 2020).

Numerous studies (Cerda et al., 2020; Favarato et al., 2014; Fernandez et al., 2010; Gohlke et al., 2000; Shakoor et al., 2021; Vincent-Caboud et al., 2017) have highlighted the positive aspects of direct seeding (DS) as listed above. In a study examining the effects of both traditional tillage (TT) and DS methods on soil organic matter content, it was discovered that soil organic matter accumulation on the surface was 130% higher in areas where DS was applied compared to those where TT was used (Feng et al., 2003). Notably, the DS method requires only one pass through the field for sowing, while the TT method typically necessitates at least two or more passes. Fewer passes translate to lower depreciation costs. In terms of fuel consumption, DS can yield an average fuel savings of 31.5 L per hectare per year compared to TT. In the context of annual crop cultivation under Southern European conditions, DS can lead to cost reductions ranging from 40€ to 60€ per hectare for different crops (Çanakcı et al., 2010).

In a pioneering study, it was found that the average soil loss was 1.16 tons per hectare per year in plots plowed at an appropriate moisture level without burning stubble after wheat harvest. In contrast, this value was calculated as 2.73 tons per hectare per year for plots where stubble was burned and then immediately plowed (Avşar & Kanburoğlu, 1996). These studies collectively demonstrate the environmental and economic benefits associated with the adoption of the DS method in agriculture.

As demonstrated by the examples provided above, direct seeding (DS) offers numerous advantages. However, it is essential to acknowledge that DS also comes with certain disadvantages, including:

(i) The need for expensive and diverse equipment, which requires a high initial investment.
(ii) The requirement to use special sowing machines to prevent potential toxic effects resulting from the contact between stubble residues and seeds.
(iii) The necessity to combat emerging weeds since the soil remains uncultivated.
(iv) The need for farmer training, as the direct seeding system involves a new and dynamic approach that demands a high degree of management capability.
(v) Long-term experiences have revealed that farmers encounter various challenges in the direct seeding system, including the use of different techniques in fertilization, spraying, and weed control (Yalçın et al., 2003).

One significant issue to address for the success of DS is the control of voles. Without proper vole control, the pits they create in the field can disrupt the operation of direct seeding machines, leading to significant problems. Another crucial consideration in the direct seeding (DS) system is weed management. Achieving success in DS relies on effective chemical weed control. Additionally, it is important to note that DS may not be suitable for crops that typically require manual hoeing, particularly in arid and semiarid regions. If there are challenges with germination due to excessive stubble accumulation, it may be necessary to disperse the stubble using a rake. Proper crop planning and pattern adjustment are essential to maximize yields in direct seeding, making it a critical aspect of the practice. Crop rotation also holds significant importance within DS systems. Patience is a virtue in the DS system. The primary goal of direct seeding is to preserve the soil for sustainable agriculture and maintain ecological balance. While it may appear costlier in the short term, farmers who prioritize these long-term benefits will ultimately emerge as winners.

4 Direct Seeding Studies in Yozgat City, Turkey

Yozgat city is situated in the heart of Central Anatolia, Turkey. This region, characterized by a semiarid climate, receives an annual total precipitation of 413 mm (1991–2020) and experiences an average annual temperature of 12.6 °C (1991–2020) (TSMS, 2022a, 2022b). The average altitude above sea level in this area is approximately 1200 m. It is predominantly a grain-producing region, with a focus on wheat cultivation. Due to limited water resources and challenging climatic conditions, crops in this region can only be harvested once a year. Despite legal regulations, penalties, and numerous awareness campaigns, farmers often resort to the practice of burning crop stubble (Yakupoğlu et al., 2022).

Stubble burning poses a significant risk of forest fires, particularly in areas near forests. To mitigate this risk, the Yozgat Directorate of Provincial Agriculture and Forestry, under the Republic of Turkey Ministry of Agriculture and Forestry, has organized numerous seminars. These seminars emphasize the importance and benefits of adopting the direct seeding (DS) method and aim to encourage farmers to choose DS over stubble burning. As a motivational incentive, farmers receive a certificate of participation after attending these seminars. Additionally, field meetings are organized, where various activities such as planting, fertilizing, and harvesting are carried out. During these events, leading farmers share their experiences with DS, further encouraging others to adopt this sustainable practice. These initiatives are conducted through collaboration between the aforementioned organizations and the Yozgat Bozok University Faculty of Agriculture.

For visual reference, Fig. 1 provides images from village seminars and field meeting days.

One of the significant challenges in convincing farmers to transition from traditional tillage (TT) to conservation tillage (CT) and to adopt direct seeding (DS) instead of burning stubble is their resistance to innovation. Farmers often prove

Fig. 1 Some pictures showing DS narration and demonstration work in Yozgat, Turkey

Table 1 Comparison of conventional tillage and direct seeding in terms of yield of some plants under rainfed conditions in Yozgat, Turkey

Plant	Regional average yield under conventional tillage system (kg da^{-1} $year^{-1}$)	Direct seeding average yield at the end of the 3rd year (kg da^{-1} $year^{-1}$)
Wheat	300	425
Vetch (hay yield)	275	550
Chickpea	100	142
Lentil	80	160
Triticale	200	238
Barley	300	350

reluctant to change established practices. Conversely, local farmers are keen to see immediate financial returns from DS. However, the expected increase in DS yield depends on various factors, including climatic conditions, soil characteristics, and management practices such as fertilization, irrigation, and herbicide application. It is worth noting that in certain cases, the product yield achieved through the CT method may surpass that obtained through reduced tillage (RT) and DS methods (Videnovic et al., 2011).

Table 1 provides the average yields of fields treated with traditional tillage (TT) and fields treated with direct seeding (DS) over a three-year period for various crops. According to the table, in Central Anatolian conditions where the TT system was applied and rainfed cultivation was practiced, the average wheat yield stood at 300 kg per hectare per year. However, this figure increased to 425 kg per hectare per year with the adoption of DS management. Similar substantial increases in yield are also observed for other crops, such as lentils, where the increase is exactly double. It is important to note that the DS data presented in the table represent yields three years after the initiation of DS. Rapid increases in yield immediately after transitioning to DS are unlikely.

5 Conclusions

While current legislation in Turkey promotes the sustainable management of soil resources, many farmers continue to burn stubble for various reasons. Despite legal regulations that align with the United Nations' Sustainable Development Goals and the Challenge of Land Degradation Neutrality, these practices persist, especially in arid and semiarid regions where rainfed agriculture is prevalent. Stubble fires not only have adverse effects on the physical, chemical, and biological properties of the soil but also carry the potential to escalate into uncontrollable wildfires. Instead of resorting to stubble burning, a more environmentally friendly and sustainable alternative is the adoption of the direct seeding (DS) system. By embracing DS, forest fires triggered by stubble burning can be mitigated. However, achieving increased productivity per unit area through DS hinges on several factors. These include the correct application of fertilization, irrigation, crop rotation, and weed control programs, as well as the selection of the most suitable plant varieties for the region, the use of high-quality seeds, and the implementation of chemical control measures against voles.

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Wildfire Education: A Review Across the Globe

Renata Pacheco, Iryna Skulska, Ana Catarina Sequeira, and M. Conceição Colaço

Abstract Recent projections suggest that wildfires will occur more often and with higher intensity due to the changing climate. In this context, it is vital to educate the population to be ready and prepared to deal with these events. This book chapter reviews the state of the art of educational materials on wildfires worldwide that are available online. A total of 225 references on the matter were retrieved. The materials are from all five continents, involving 36 countries and written in 23 languages. Most of them are from regions with a Mediterranean climate with fire-prone ecosystems in which, for the last decades, wildfires have negatively affected the population. Regarding the target audience, most materials retrieved focused on the general public (about 48%), followed by students from various age groups (around 40%). Written documents, websites, and videos are the most frequent materials for the general public. As for students, a greater variability of pedagogical materials is available, ranging from mobile phone applications and digital and experimental activities to slides for classes and reading materials. The remaining materials focus on the rural population and firefighters' training. Most references present the main concepts and ecological aspects of fire, along with safety and prevention measures. However, few discuss climate change, recovery, and socio-economic or health concerns. This gap should be addressed in the future wildfire educational materials to better prepare and inform society.

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Keywords Fire pedagogy · Environmental education · Climate change · Wildfire resilient societies · Fire education resources · Sustainable future · Fire education contents

1 Introduction

Predicting the future of the planet under the influence of climate change is among the most pressing issues of our time, along with understanding its impacts on our civilization (McNutt, 2013). Furthermore, climate change might increase the challenges linked to environmental, social, and economic changes (Keenan, 2015), such as the recurrence and intensity of large wildfires, the escalation of people migration, and the loss of biodiversity. These risks and impacts will manifest globally, as few cultures and territories will escape their influences in coming decades, whether in cities in the developed world or resource-dependent subsistence economies (Adger et al., 2013; Plana et al., 2021). Adapting to climate change requires understanding the role of climate on the ecosystem, industries, and communities. This requires multiple forms of knowledge and new approaches to management decisions in various sectors, including forest management (Keenan, 2015).

In what concerns wildfires, more extreme and frequent events are among the challenges posed by climate change, as seen in recent decades worldwide (Amatulli et al., 2013; IPCC, 2022). Also, IPCC (2022) reflects on the increase in the fire season, particularly in the Mediterranean climate. In recent years, catastrophic wildfires occurred worldwide, affecting particularly the life and safety of thousands of people (fatalities, injuries, and evacuation from their homes), putting in plain sight the need for a more aware and educated society to face this risk (Fernandez-Anez et al., 2021; Grant & Runkle, 2022; Molina-Terrén et al., 2019).

Education plays a key role in the prevention and preparedness for wildfires (Colaço et al., 2018; Pardellas et al., 2018). Education influences how responsible institutions and individuals deal with certain issues related to various risks and make long-term changes. In addition, in many cases, education works well with the public and prevents emergencies before they happen (Knox, 2018). Wildfire education efforts encompass various methods, including public service announcements, distributing brochures, and making presentations, which are intended to prevent and/or mitigate negative fire consequences (Prestemon et al., 2010). Simultaneously, several pedagogical campaigns focusing on students and teachers or inhabitants in risk areas occur in different countries (Colaço, 2017). However, in the face of this new reality, where extreme fire events surprised communities and different authorities like Forest Services or Civil Protection Agencies (Portugal 2017, Greece 2018, Chile 2018, USA 2017, Australia 2018), the need for more information and education became very clear.

Considering this pressing demand to inform and educate the population about the need to adapt and prepare for wildfires, especially in the context of climate change, the present book chapter aims to review the wildfire educational materials state of the art worldwide. Additionally, limitations and suggestions for future wildfire educational content are made.

2 Materials and Methods

Online searches were conducted to find and select the wildfire and forest materials to be included and analyzed in this review. The searches took place between July and September 2022. The keywords “forest”, “fire”, “wildfire”, “educational”, “didactical”, “pyrology”, “forest fire guide”, “guide”, “manual”, and “handbook” were typed into Google’s search engine (social networks posts were not included in this study). The previous terms were associated in multiple ways to maximize the number of retrieved results (e.g., “forest” + “wildfire” + “handbook”; or “forest fire” + “educational” + “guide”). Following a snowball literature search type method, in which previous results inform the next searches (Lecy & Beatty, 2012), more results were found from new web links and bibliographic references.

The search was aimed at finding literature for all possible audiences: schoolchildren, students, firefighters, technicians, as well as general public. In order to get more accurate results on a global scale, the searches were conducted in the following 21 languages, as they were the ones the authors were able to read: Bulgarian; Czech; English; Estonian; Finnish; French; German; Greek; Icelandic; Italian; Kazakh; Latvian; Mongolian; Polish; Portuguese; Roman; Russian; Spanish; Swedish; Turkish, and Ukrainian. Additionally, Catalan, and Galician references were also included although the languages were not explicitly searched, totaling 23 languages.

Next, a document analysis was used to examine the general content of the educational material retrieved. This is a systematic procedure applied in the review or evaluation of documents, such as institutional programs. As a research method, document analysis is applicable to produce detailed depictions of a single program or policy (Bowen, 2009), which constitutes an adequate approach for this study. The characterization of the content was done according to the information given in Table 1, which was developed to structure the document analysis. This characterization did not address the quality of the documents, it only describes the subjects presented in the materials.

Next, the results of the content analysis process are shown. The main trends identified are described, and the knowledge gaps are highlighted in the discussion. Finally, based on the analysis results, suggestions on the way forward for forest and wildfire education are made.

Table 1 Topics examined in the document analysis performed in the review process

Topics analyzed	Categories
Country	Country for which the content was developed
Target audience	• General public • Firefighters • Students[a] – Pre-school (ages from 4 to 5) – Elementary school (ages from 6 to 10) – Middle school (ages from 11 to 16) – High school (ages from 17 to 18) – K-12 (ages from 4 and 18) – College (over 18) • Rural population
Material format	• Written documents • Video • Website • Activities • Slides • Book (written documents with an International Standard Book Number-ISBN) • Phone application (APP)
Subjects	• Climate change • Ecological aspects of wildland fires • Economic concerns • Fire effects • Fire management • Fire mitigation • Fire prevention • Fire regimes • Fire risk • Fire safety • Fire triangle • Health concerns • History of humans and fire • Legislation/policy • Main fire concepts • Recover • Response • Social concerns • Uncontrolled fire versus controlled fire

[a] Since school names and structure change according to the local educational system, the age range considered in this study is indicated

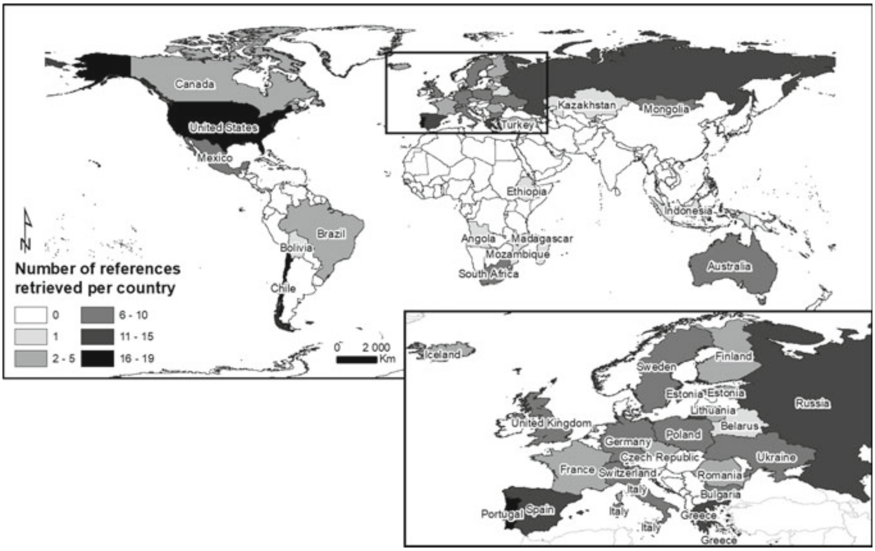

Fig. 1 Number of references retrieved per country. Searches were conducted on Google between July and September 2022

3 Results

After three months of online search using multiple associations of the established keywords, a total of 225 references on wildfire education were retrieved from the five continents.[1] Figure 1 shows the number of references found per country.

Materials were found from 36 different countries, as well as two references that dealt with global wildfire issues. Then, the target audience for each of the materials was analyzed. Some of them were focused on specific groups, such as the firefighters and rural population, while others targeted broader audiences. Figure 2 shows the distribution of the retrieved references according to their target audiences.

Most of the information and educational materials found were targeted at the general public (about 48%), followed by students from various age groups (around 40%). The other more specific target groups accounted for around 11% of the total. Some materials were intended for more than one group, such as firefighters and the general public. As for the format of the educational references, there were multiple mediums and sets of materials. Figure 3 shows the distribution of the total retrieved content format and its associations.

Most of the educational content is presented exclusively in a document written form (about 44%), usually through a wildfire guide or manual. Websites are also a common mean to share educational content (about 30% of the references). More

[1] Spreedsheet with all references available here: https://tinyurl.com/WildfireEducation.

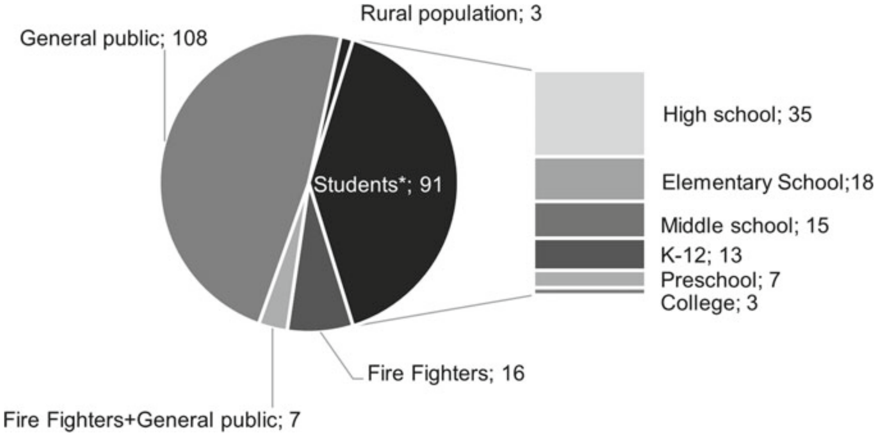

Fig. 2 Distribution of the total retrieved materials according to their target audience. *Students: Pre-school (ages from 4 to 5); Elementary school (ages from 6 to 10); Middle school (ages from 11 to 16); High school (ages from 17 to 18); K-12 (ages from 4 and 18); and College (over 18)

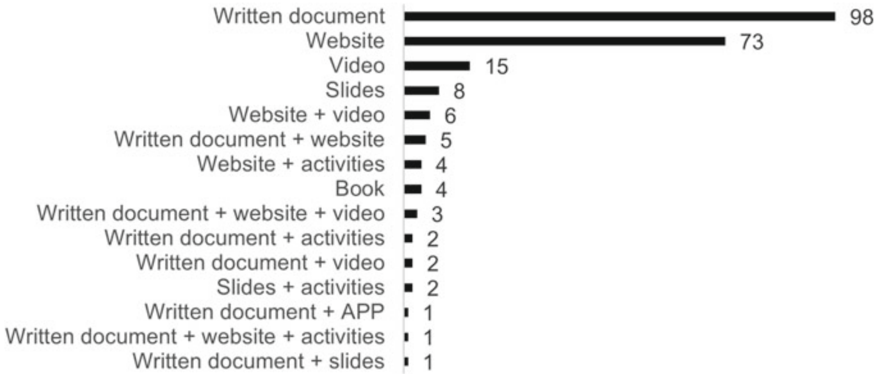

Fig. 3 Distribution of the formats in which the educational materials are provided

modern means of information sharing, such as phone applications, were not retrieved often.

Regarding the topics addressed per reference, it was possible to analyze the content of 218 materials, as a few of them were paid or not fully available online. Most of them encompassed multiple issues varying from the basics of fire chemistry up to fire safety and policy issues. Table 2 gives the percentage of educational materials that addressed each of the topics.

Most materials cared to describe the main concepts and ecological aspects surrounding wildfire occurrences. Fire safety, prevention, and risk were also among the most addressed topics. Issues related to climate change and socio-economic matters had the least focus among the retrieved materials. Finally, it was possible to

Table 2 Topics addressed by the retrieved didactical materials

Topics	% of references (%)
Main concepts	65
Ecological aspects of wildland fires	56
Fire safety	55
Fire prevention	53
Fire risk	53
Fire management	46
Fire regimes	38
Response	32
Fire triangle	28
Fire effects	26
Fire mitigation	22
Uncontrolled fire versus controlled fire	21
Legislation/policy	17
Climate change	16
Recover	14
History of humans and fire	12
Economic concerns	10
Social concerns	9
Health concerns	7

determine the date of 216 references that were made available. It was observed that they were all released between 2000 and 2022 (Fig. 4).

It should be highlighted that most of them (around 83%) were developed in the last ten years. Moreover, it is possible to note that after 2017, a year with major wildfires in places such as Portugal and California, the number of materials released shows an increasing trend.

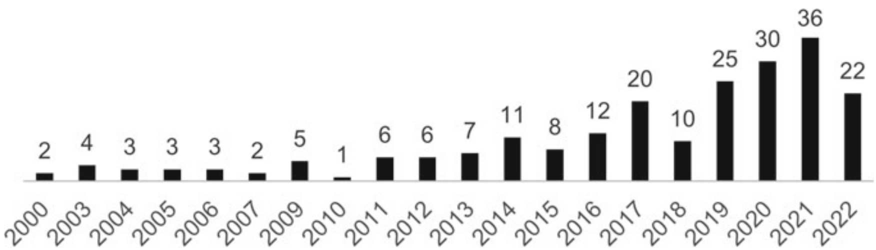

Fig. 4 Distribution of the release year of the wildfire educational materials retrieved

4 Discussion

About 40% of the retrieved educational materials were elaborated in countries that have experienced recent and intense wildfire events, namely the USA, Portugal, Chile, Russia, Spain, and Greece (BBC, 2017; Dixon, 2021; Euronews, 2022; Firstpost, 2017; NIFC, 2022; Voanews, 2022). Also, in terms of the distribution per country, more than 50% of the references are from nations with Mediterranean-climate regions. These regions are present in all five continents (Rundel, 1998). Although they only occur on about 2% of the world's total land area (Dallman, 1998), these climatic regions are major centers of human population (Montenegro et al., 2004) with major economic damages due to wildfires (EM-DAT, 2022). Regarding its global land area distribution, Mediterranean-climate regions are 73% in the Mediterranean Basin, 10% in California; 10% in Southwestern Australia; 4% in Central Chile; and 3% in the Cape region (Rundel, 1998). The content retrieved per country in the search process follows this proportional distribution. This reinforces that these areas have a higher demand for educational materials targeted at their ecosystem reality, as they are fire-prone, and most are densely occupied by infrastructure and human population. In contrast, no references were found for countries like Latvia, which was targeted in this study's search. Perhaps, since the occurrence and area affected by wildfires have decreased in the last decades (GWIS, 2022), despite that the total area of forest land has nearly doubled (Donis et al., 2017), it has not created a demand for educational material on wildfires in Latvia.

As for other regions of Europe, the least information was found in the Nordic and Baltic countries. Among the Scandinavian countries, the largest amount of material was found in Sweden. Considering the dates of the publications from this country, they are likely a response to the wildfires that raged through large parts of Sweden in the summer of 2018 (Krikken et al., 2021). Another interesting fact is the quantity of material found in Central European countries, namely Germany and Switzerland. Nine sets of education materials found in Germany and six in Switzerland contain extensive information on many of the analyzed subjects. This can be explained by the strong forest tradition in these countries and their concern about climate change and wildfires.

As for the target audience, almost half of all found and analyzed references (about 48%) are aimed at the general public. Most of these materials are guides, manuals, websites, and a few videos. They mainly present basic wildfire concepts and focus on wildfire prevention and safety issues related to their community context. As programs that tailor their efforts to tackle local values and interests are more likely to be adopted (Sturtevant & Mccaffrey, 2003), it is interesting to observe that despite having similar information, most of the references tried to contextualize their content to reflect their local reality.

The next large target audience for wildfire educational materials are students (about 40%). Of the materials aimed at students, around 38% are specifically focused on the high school public (17–18 years of age). This can be explained by the larger capacity to address complex problems, their willingness to change the world (e.g., climate strike), and also by the benefits related to academic achievement and civic engagement (Ardoin et al., 2018). Furthermore, some of these materials include activities effortlessly integrated into the curricula of many disciplines of this level of education.

Very few references target the rural population. Perhaps, since the searches for this study were conducted online, some materials aimed at this parcel of the population were not retrieved. As this public is not necessarily technological-savvy, likely, educational materials that target them are not presented in a digital form. However, considering that many wildfires worldwide ignite in a rural setting, perhaps more effort should be put into communicating with this parcel of the population through multiple means, as it could potentially directly result in a lower number of fires and lead to better preparedness. In general, the communication means for rural communities are presented in paper brochures or posters, distributed door to door, and professional and popular fairs (Colaço et al., 2018; Pardellas et al., 2018).

As for the format in which the educational content is presented, most references rely on digital written guides, manuals, handbooks, or websites. This is especially the case when they target the general public. Few materials stimulated the public to interact with their local community and promote active forest and fire management and preparedness. In some cases, communication channels were indicated to engage the population further.

In contrast, a wider variety of means is observed when the target audience is students. This is probably pedagogically adequate, as the younger generations are digitally fluent, competitive, and are considered digital natives. Thus, transmitting knowledge, teaching, or reinforcing skills can use various digital didactic tools, like e-learning platforms, games, intelligent accessories, and instructional videos (Gawlik-Kobylińska et al., 2020). For this parcel of the population, more interactive activities were provided, including complete classroom lesson plans (CIRES, 2022). Even companies in the private forestry sector have developed interactive educational materials aimed at school-age children (Navigator, 2020). Furthermore, classical characters, such as Smokey Bear, appear in materials targeted at almost all age groups (USDA, 2007). The need for a mascot that represents a "cute" and "loved" animal continues to be used in different wildfire prevention campaigns (e.g., Raposa Chama (Portugal) with a fox, Mefitu (Spain) with a wolf or Bookie (South Africa) with a klipspringer).

For this study, the quality of the content provided in each reference was not analyzed. The goal was to map the main concerns and recommendations being conveyed to the various sections of the population. The results indicate a widespread concern about transmitting the basic knowledge regarding wildfire chemistry and physics and providing basic prevention and safety knowledge.

However, not many references tackled issues of a socio-economic nature. This is potentially a shortcoming of the educational references available, as people do not tend to expect to lose a house to wildfire, and showcasing the social benefits of adopting fire prevention measures may be more effective than highlighting only economic advantages (Sturtevant & Mccaffrey, 2003). This is perhaps a changing reality as recent fires in many parts of the world have caused substantial material losses and many lives were lost. This might push for the development of more educational materials, including socio-economic issues related to wildfire prevention. Furthermore, programs that promote contact between neighbors can aid in developing a sense of community as they work collectively to lessen fuels across ownership boundaries (Lisa Langer & McGee, 2017; Sturtevant & Mccaffrey, 2003). A few community programs consider this, such as FireWise and FireWorks in the United States and FireSmart in Canada.

Finally, considering that most references were made available to the public in the last ten years, it is interesting to note that very few addresses climate change and its consequences for forest and fire management, as well as the history and culture of fire. This can also be considered a notable gap, as adopting principles and practices of sustainable forest management can provide a sound basis for addressing the challenges of climate change (Keenan, 2015), especially in the context of wildfires.

5 Conclusion

This study provided a content overview of the current state of the art of wildfire educational materials from 36 different countries. The diversity and content of the found materials, as well as their ability to satisfy the search for information about wildfire from an educational point of view, were analyzed. It was beyond this study's scope to analyze the content's quality but rather to map the type of information being communicated to the public. The results have shown that wildfire is a concern in all five continents, as fires eventually happen in every country. Nevertheless, more materials are available in developed and highly populated places with fire-prone ecosystems, such as Mediterranean-climate regions, suggesting the need to tailor the educational content to the local culture. Regarding the materials content, the most innovative approaches were targeted at students. Possibly, this is linked to the fact that this parcel of the population is more predisposed to learning and is familiar with more modern technologies. As the content search was conducted online, it is not surprising that the more advanced resources target a younger audience. Still, the general public could also benefit from more information content being available in multiple media. Furthermore, initiatives targeting not only individuals, but the entire community might be more successful, especially regarding fire safety.

Moreover, there was a lack of content regarding wildfire's socio-economic aspects, including health and trauma issues. Furthermore, considering that most references are from recent years, it is surprising that climate change is not one of the most addressed issues, as evidence indicates that it is one of the issues that is affecting fire regimes. As cultural perspectives partly explain the differences in responses across populations to the same environmental risks, and recent research shows that information about climate change does not connect with all cultures and worldviews in the same way, contextualization becomes essential. The development and adaptation of educational materials on wildfires at the local level become a fundamental step in managing this risk and mitigating its consequences for society.

Finally, the literature suggests that wildfire education efforts appear to have persistence in the population, and some initiatives, such as Smokey Bear, have sensitized generations, which reinforces the importance of investing in the development of didactical/informational materials. In this sense, the present study has provided insights that can inform the development of wildfire educational content that is meaningful both from a broad and general perspective, as well as considering local cultural aspects.

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Forest Fire Risk Management at the Country Scale: The Case of Turkey

Yaşar Selman Gültekin and Pınar Gültekin

Abstract Forest fires cause hazards and damage to both ecosystems and humans increasing attention in the globalizing world. Forest fire risk analysis and management issues cover the prevention of forest fires, response to forest fires and what to do after the forest fires. This chapter is focused on the evaluation of forest fire risk management from socio-economic, landscape planning and risk management perspectives at the country scale. In this context, national policies, strategies, documents and practices are scrutinized in terms of forest fire mitigation acts in Turkey. As a result of the examination policy makers and decision-makers should increase pay attention to their primary stakeholders for better engagement in forest fires. There is an urgent need to obtain an annual forest fire risk assessment report from public institutions. Participatory approaches need to be applied through good governance to mitigate forest fires and decrease forest fire risks in Turkey.

Keywords Participation · Stakeholder engagement · Good governance · Turkey

1 Introduction

Wildfires are widespread in many regions over the world due to several causes such as urban sprawl, the extensive land abandonment in the late twentieth century or mismanagement of natural areas that led to increased frequency and severity of wildfire risk (Moreno et al., 2021; Fernandez-Anez et al., 2021). This has increased the risk of human and economic losses, changes in vegetation cover, surface runoff, soil degradation and contamination of the water bodies of streams, and reservoirs with toxic compounds in ashes (Terêncio et al., 2020). Fire is a natural phenomenon that affects Earth's ecosystems and which needs better research networking to face the

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challenges of scientific development and fire risk management (Stoof & Kettridge, 2022). Fire dynamics and behavior are essential to understand fire prevention and predicting the environmental impacts of fires (Mueller et al., 2020). Building an understanding of the types of fire behavior (energy release, spread rates and conditions of extinction) that occur in our changing landscapes such as abandoned agricultural sites and across newly connected ecosystems is substantive if we are to effectively manage fire prevention and emergency responses to fires in these areas (Samuela Bassi, 2008).

The risk concept widely defines the possibility of something bad happening. Risk refers to uncertainty about the effects/implications of an activity concerning something that humans value (such as health, well-being, wealth, property or the environment), often focusing on negative, undesirable consequences (Hardy, 2005). Accordingly, forest fire risks can be defined by the possibility of various criteria coming together in an area to cause a forest fire (Baltaci, 2021). To manage forest fire risks sustainably, it is key to define potential risks, and then, analyze and evaluate them according to scientific criteria (Çoban & Erdin, 2020). Moreover, under climate change and shifting biogeographic vegetation patterns, novel fire behavior begins to affect regions that have not previously had a significant fire history or fire management infrastructure (Elvan et al., 2021). On the other hand, increasing the living standards of local people dramatically reduce fire risk (Samuela Bassi, 2008).

According to the assessments regarding the climate crisis, it is predicted that the frequency of forest fires will increase in the future all over the world due to extreme heat and drought (IPCC, 2021). Therefore, an understanding of fire dynamics in Europe's climate and ecosystems is required as well as coupled research on emergency response (onsite and offsite) and monitoring, mapping, and adoption of new firefighting strategies and decision-making strategies to manage, prevent, combat and fight forest fires that might display a range of fire behaviors. All these issues require a holistic approach to sustainable fire management (Abreu, 2022).

Turkey has been struggling with forest fires, especially in the Mediterranean regions of the country. It has been deeply affected by mega-forest fires in 2021 and raises awareness of forest fire risks and mitigation strategies in scientific and socio-political areas. Mega-forest fires have been recently defined by United Nations Environmental Program (UNEP) as "an unusual or extraordinary free-burning vegetation fire which may be started maliciously, accidentally or through natural means, that negatively influences social, economic or environmental values" (UNEP, 2021). This situation shows that we are facing some different challenges. Financial investment and human and organizational resources are required to minimize the negative impacts of forest fires (Mavsar et al., 2012). However, new approaches and perspectives are needed for forest fire risk assessment and management.

In this book chapter, we present as a main aim, an example of research to show how to evaluate damages caused by forest fires, costs and their reasons from socio-economic, landscape planning and risk management perspectives at the country scale using Turkey. Policy implementations were also presented to evaluate the fire risk management practices in this country. The political framework, socio-economic constraints, ownership and legal issues will be evaluated to assess the forest fire risk management issues and how local features can be overcome, and transferability allowed among different EU contexts.

2 Forest Fire Risk Analysis in Turkey

The fire risk concept is still under investigation by some researchers but some key variables can explain the underlying factors of forest fires (Çoban & Erdin, 2020; Çolak & Sunar, 2020; Daşdemir et al., 2021; Hardy, 2005). Forest fires may be the result of natural phenomena, human negligence, accidents and human intentional behavior. There are two main causes of forest fires in Turkey: "thunderbolt" and "human" (GDF, 2022). Although the number of these two reasons varies per country, in Turkey, 1% of forest fires are caused by thunderbolts. Thunderbolt apart from fires with few numbers, the main cause of fires is human "human factor" which is always the main problem in fire protection (FAO, 2007; Samuela Bassi, 2008). According to studies on forest fire risk resources, tourists and local people living in or adjacent to forests cause forest fires due to socio-economic reasons, low level of education, stubble burning, agricultural activities, tourism and recreational activities, illegal utilization, intentional, negligence, lack of knowledge and awareness, etc., in Turkey (Çolak & Sunar, 2020; Gültekin & Baysal, 2020; Sezgin & Gültekin, 2022; Yakupoğlu et al., 2022; GDF, 2022).

After analyzing scientific papers, there are major motivation types such as agricultural burning, rangeland intentional burning, pyromania, hunting, vandalism, getting salaries, non-planned land use changes, revenge, dispute against punishments, resentment against reforestation, grazing, watching forest fire fighting, distract the police, rituals, cancelations contracts with administration or resentment against subsidies (GDF, 2022; Sezgin & Gültekin, 2022; Yakupoğlu et al., 2022). Despite all the opportunities provided by ecosystem services, it can be said that the desire of human beings to make excessive use of forest resources constitutes the basis of forest fire risk resources (Samuela Bassi, 2008). In order to reveal the social and economic consequences of forest fires, it is necessary to focus on the economic benefits of forests, in other words, the functions of forests. Contemporary studies mentioned that ecosystem services are a key issue to understand and manage forest ecosystems (Başak et al., 2022; Gültekin, 2022).

Forest fire statistics (General Directorate of Forest, GDF) have been regularly collected and degrees of fire risks mapped to combat and monitor the forest fires in Turkey. Damages caused by forest fires and their reasons should be evaluated according to burnt areas from the forest fire risk management perspective (Fig. 1).

Forest fire risk factors that can be considered are topography, wind speed, high temperature, low level of humidity, accelerators (i.e., low moisture content of combustible material, especially coniferous species), the existence of large and uniform areas, where the accumulation of fine combustible material is very high (Çolak & Sunar, 2020). According to forest fire statistics, total burnt forest areas explicitly increased in recent years (Fig. 2). Unfortunately, there is still not enough

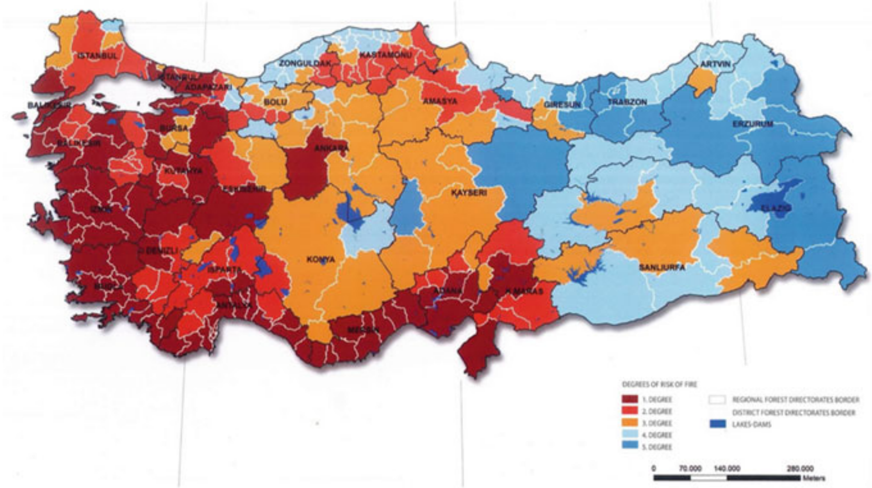

Fig. 1 Forest fire risk map of Turkey. (Risk ranges from "1°" = Highest to "5°" = Lowest. Graphic: GDF, 2022)

scientific evidence to understand forest fires and their underlying risks in Turkey (Fig. 3). It is hard to decrease the forest fire risk because of causing forest fires 48% "unknown" according to statistics of GDF (GDF, 2022). Although the annual number of fires does not change much over the years, the increase in the total burnt area is remarkable.

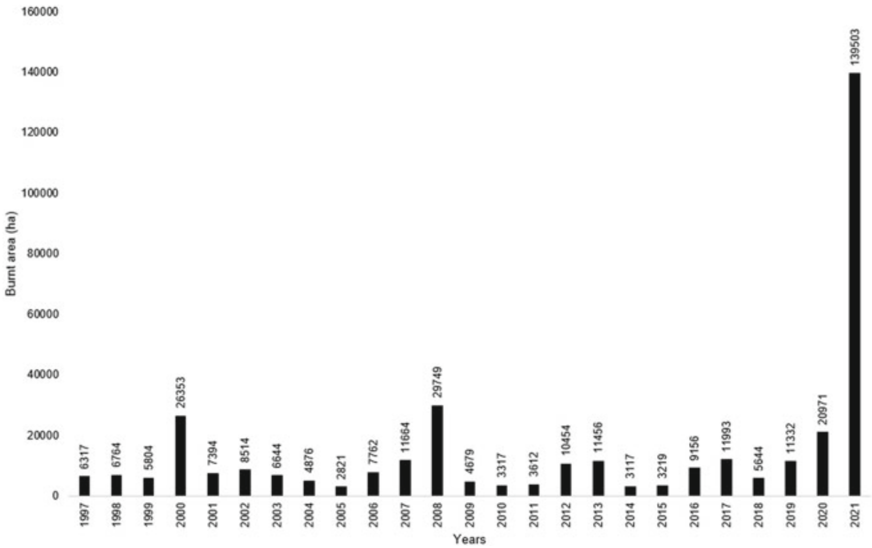

Fig. 2 Forest fire statistics according to burnt areas between 1997 and 2021 in Turkey (GDF, 2022)

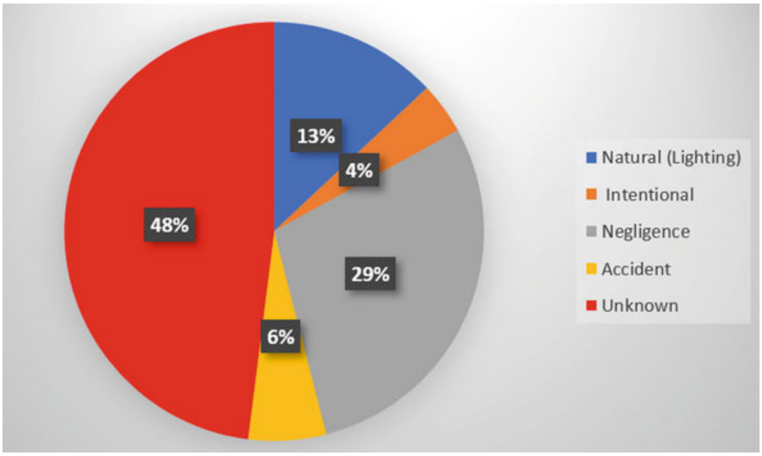

Fig. 3 Causes of forest fire in Turkey (GDF, 2022)

3 Forest Fire Risk Management in Turkey

According to the Turkish constitution (article no. 169) and law (article no. 6831), all forest areas are managed and controlled by the government via the Ministry of Agriculture and Forestry. GDF follows sustainable forest management principles according to the national forestry program (2004–2023) and GDF strategic plan (2019–2023) as a public institution affiliated with the Ministry of Agriculture and Forestry. GDF applies "Forest Fire Prevention and Combat Acts" including fire risk maps, forest fires early warning systems, forest fire towers, and fire pools (GDF, 2022). In this regard, the "Fire Management System" has been used by GDF since 2007 (Fig. 4).

Fire prevention facilities are being built within the scope of Fire-Resistant Forest Projects (YARDOP) projects started in Turkey. Neyişçi (2011) mentioned the use of some species in forest areas such as *Cuppressus spp.* can be effective to mitigate forest fires in the Mediterranean region of Turkey. The use of fire-resistant species in forest areas can decrease the risk of forest fires of severity and sprawling. As of the end of 2020, a total of 8358 km of fire prevention facilities (i.e., fire breaks, plantations

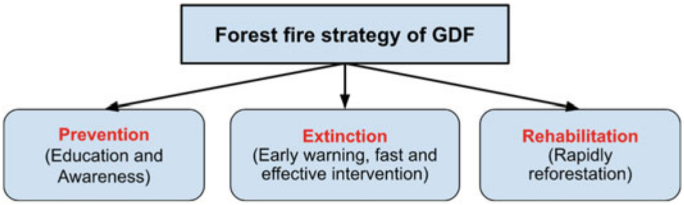

Fig. 4 Forest fire strategy of general directorate of forestry (GDF, 2022)

Table 1 Forest fire extinction activities of GDF in Türkiye

Forest fire extinction activity	Amount	Forest fire extinction activity	Amount
Forest fire rangers	20,500	Drone	10
Forest fire towers	776	Dozer	181
Fire extinguisher equipments: water-tender	1010	First responder team	1167
First responder vehicle	2270	Firefighting aircrafts	3
First responder team	1167	Other vehicles	501
Helicopters	39	Water tender	281
Forest fire volunteers	13,400		

of fire-resistant species, pruning of trees near the roads, etc.) have been applied. YARDOP application was made in 292,719 ha forested areas in Turkey (GDF, 2022). Forest fire costs (direct costs) are explained as 45 million Euros according to the GDF budget report in 2020. There also 8 people died because of these forest fires in Turkey (GDF, 2022). Unfortunately, there are no indirect cost calculations such as biodiversity and tourism losses, injuries, non-wood products loss and wildlife loss after forest fires in Turkey. According to the legislation of GDF, circular cleaning and harvesting activities are mandatory after forest fires in Turkey (GDF, 2022) (Table 1).

Disaster and Emergency Management Presidency (AFAD), affiliated with the Ministry of Interior, appears as the highest level and sole authority in terms of disaster preparedness and response in Turkey. AFAD prepared disaster prevention, coordination and response plans for the first time in 2014 within the scope of the "Turkish Disaster Response Plan" (TAMP, 2014). However, due to the mega-forest fires in recent years, it has been observed that there are major problems in coordination between institutions and in the fire response process. For this reason, it is necessary to review fire risk management at the national, regional and local levels in Turkey.

4 Discussion and Final Remarks

In Turkey, many citizens cause forest fires by having recreational activities in the forest areas because of their carelessness and neglect. Participation of citizens is a crucial issue in terms of motivation factors to prevent forest fires (Land-Zandstra et al., 2021). Citizen science approaches can be used to decrease forest fire risk and combat forest fires. Forest villagers can be included as volunteers to contact GDF in the early warning system. Local people can be involved in communication platforms or networks (Mavsar et al., 2012). This approach can be decreased the involvement duration of forest fires in shorter minutes.

However, there are forest fires because pedestrians and transportation roads pass through the forests. Some forest fires can cause thousands of hectares of forest area to burn as a result of a spark from just one train (Niklasson et al., 2010). The presence of 21 thousand of villages in and adjacent to forests in Turkey and the fact that approximately 7 million people live in these forests increases the risk of forest fires. As a result of the Antalya-Manavgat fire, which was recorded as the largest forest fire in Turkey in the recent past (in 2020), nearly 59.000 hectares of total forest areas have been burnt (GDF, 2022). Lack of coordination and cooperation between stakeholders increases the forest fire risk. Stakeholder engagement and participation need to be provided through good governance (Gültekin, 2022). Forest fire action plans need to be improved and up to date in terms of sustainable forest fire management (Daşdemir et al., 2021).

There is a need to improve prescribed forest fire risk management, more critically, "local people" acceptance and participation as a strategy for future land management (Francos & Úbeda, 2021). The fact that the local people do not have enough knowledge about firefighting also makes it difficult to fight forest fires. For instance, it has been observed that forest engineers who tried to intervene in forest fires that took place in recent years were physically attacked while using firefighting techniques. There is also an important key issue increasing forest villagers' quality of life that needs to be considered in risky regions (Daşdemir et al., 2021). It is clear that decision-makers need to be focused on intensive forest fire prevention studies (Taylor et al., 2019). These studies are described as less dangerous, easier, more valuable and cost-effective activities. It is a new initiative defined as the «Public Education through Mobile Education Teams» project which can be a good practice in Turkey (GDF, 2022). Especially GDF need to find and apply smart, effective and practical solutions for the pre-fire activities in Turkey (Çolak & Sunar, 2020).

Intensive education programs on fires are required (Charnnarong, 2021). For example, it was determined that some of the people living in the forest lost their lives in the Antalya-Manavgat fire because they did not want to leave their homes (GDF, 2022). This shows that there is a need for more effective information and awareness-raising studies and projects about the extent of the danger, especially wildfires.

It is necessary and should be possible to inform forest villagers and farmers through documentaries, TV programs, education and training activities, social media activities, etc., about the necessity and benefits of forest assets and to make them more familiar with forest goods and services. In addition, how the villagers can obtain more income from forest resources can be explained with this approach as well. These activities are very effective but mostly invisible and hard to measure the total effect. Lack of coordination and cooperation between stakeholders should be fulfilled in Turkey. There is a new establishment and initiative necessary covering national, regional and local stakeholders leading AFAD. Crucial stakeholders include the Ministry of Interior, Ministry of Agriculture and Forestry, General Directorate of Forestry (GDF), public institutions (Universities, Municipalities, etc.), Private sector related to forest fires, NGOs, and the public (forest villagers, farmers, civil society) must gather participatory approaches (Hesseln, 2018).

To reduce the risk of forest fires, it should be ensured that species are resistant to fires to the extent permitted by ecological conditions in afforestation. It is stated that planting species such as *Cupressus sempervirens* in forest areas with fire risk not only makes the forest resistant to fires but also contributes 10–15% to the increase in volume (Coşgun & Çobanoğlu, 2009). Especially in areas where the Mediterranean climate prevails mixed with red pine in the afforestation works to be made, therefore more fire-resistant establishing forests is a highly convenient practice. In literature, especially fire-resistant species such as "*Cupressus sempervirens*" can be used for fire prevention. It is stated that Cupressus proved their resistance to flames in the Gallipoli Fire in Turkey. From this perspective, Fire-Resistant Forest Projects (YARDOP) should be enhanced in Turkey (Neyişçi, 2011; Yılmaz, 2016). The utilization of various fruit tree species such as olive, almond and walnut as buffer zones for the protection of citizens and forests from forest fires in the settlement areas will also serve the sheltering, feeding, breeding and protection from the enemies of the hunting animals in these areas. This issue must be supported and prioritized by policymakers and decision-makers in Turkey.

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Fire Management and Preparedness in the Czech Republic

Petra Martínez Barroso, Jan Winkler, and Magdalena Daria Vaverková

Abstract Fire management and preparedness in the Czech Republic (CR) is evaluated based on a broad knowledge platform consisting of official documents of the Fire and Rescue Service of the Czech Republic (FRS CR), laws of the CR, as well as scientific works from Czech universities and professional publications. The composition of the forests, mostly composed of coniferous tree species, has been conditioned by historical events and closely connects to the current health state of the Czech forests, which has been seriously affected by the bark beetle calamity. The most common types of forest fires in the CR are due to its geographical location surface fires. The main cause of fire ignition is human carelessness. The number of forest fires in the Czech Republic has an increasing tendency, however, the burnt area does not grow proportionally to the number of fires thanks to the high-quality technical equipment of the Czech firefighters and their timely response. The forest fire prevention strategy belongs to the competency of the state-owned enterprise Lesy of the Czech Republic which in cooperation with scientific institutions and universities focuses on optimizing collaboration with the Fire and Rescue Service of the Czech Republic; creation of methodologies and recommendations in the field of fire prevention; enlightenment and education of the public; and recovering the landscape capacity to maintain water. Due to changing climatic conditions, the fire regime in the CR will likely change and the current approach will need to be adjusted.

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Keywords Forest fires · Czech Republic · Fire management and preparedness · Fire and rescue service of the Czech Republic

1 Historical Background of the Current Composition of Czech Forests

The Czech Republic (CR) is an inland central European country located in a temperate zone. The current composition of Czech forests is not natural but it is a result of long-term historical development. The forests used to be a natural climax cover on the majority of Czech territory before the outset of agriculture (around 6000 BC). The development of agriculture triggered deforestation by burning them. The burning of forests took place particularly in the most fertile lowland areas and along the most important rivers. These areas are located in Polabí and Poohří in central Bohemia, and Podyjí, Úvaly (valleys) in southern Moravia (Kadrba & Bičík, 2010) where the low density of afforestation is evident up to the present (Fig. 1).

Green color represents forests (36.8%), gray color stands for agricultural land (40.8%), grass vegetation (9.4%), settlements (8.6%), water areas and wetlands (1.3%), and others (3.0%).

Original forests consisted of oaks, beeches, and firs, which covered mostly highlands and mountains. Until around the tenth century, forests covered approximately 80% of the territory (Lipský, 1999). During the twelfth and thirteenth centuries,

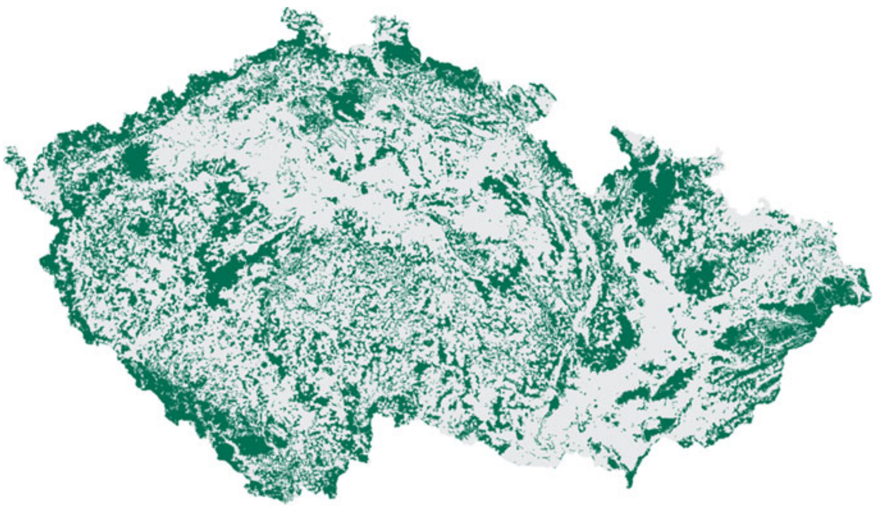

Fig. 1 Distribution of forests in the CR from author Fakta o klimatu. A modified illustration *Kde jsou v Česku lesy*? by author Fakta o klimatu, licensed by CC BY 4.0. Available: https://faktaoklimatu.cz/infografiky/lesy-cr-mapa. *Data source* Copernicus—CORINE Land Cover, National Forest Inventory (Land Use) (Kde jsou v Česku lesy, 2022)

the population grew thanks to a prospering agriculture which resulted in the expansion of settlements to less accessible areas in higher altitudes which consequently implied deforestation of these areas (Beranová & Kubačák, 2010). An important milestone regarding the area of protection of forests came in 1350 when the constitutional project, *Maiestas Carolina,* was issued and prohibited the burning of forests (Ledvinka, 2020). Nevertheless, there was no additional care for the forests, and they were used only for logging, and grazing livestock. Their regeneration took place only in times of war, from which the most significant was the Thirty Years' War (1618–1648), and during disease epidemics (Beranová & Kubačák, 2010). Since the end of the seventeenth century, forests were heavily exploited by logging due to developing industry. During the Age of Enlightenment (eighteenth century), the first forest protection laws were created, but at the same time, natural deciduous forests were replaced by coniferous species, especially spruce, due to the demand for flat quality wood for construction purposes and developing industry.

In the middle of the nineteenth century, the afforestation of the Czech lands was historically the lowest (it accounted for less than 29% of the total surface of the country) (Jemelka, 2016). The trend of deforestation changed at the turn of the century and the number of forested areas started to increase which can be attributed to three main factors. Firstly, the development of fertilizers, pesticides, and breeding helped to gain higher production in smaller areas. Areas in less favorable conditions that were not used anymore were reforested. Secondly, wood was replaced by fossil fuels for heating purposes and by iron and concrete for construction purposes. And lastly, the creation of forest protection laws—e.g., a ban on grazing in forests, a ban on building houses from flammable materials, or an order to replace every felled tree with a newly planted seedling (Kadrba & Bičík, 2010).

During the nineteenth century, forests in the borderlands, highlands, and mountains benefitted from the development of transport because food started to be imported from more fertile lowlands, where it was easier and more efficient to cultivate. The end of the conflict with the German dictatorship caused leaving of German citizens from about a third of the Czech territory after WWII which also contributed to the afforestation of the borderlands as the abandoned territory was either naturally revegetated or intentionally grassed over and afforested (Zelinka, 2021). The rise of the percentage of the forest continued growing after the fall of communism. The food market opened up to competition from abroad, and the need for local production dropped sharply which resulted in decreasing the share of arable soil. Ecological services of forests began to be recognized and agricultural and ecological policies started to support afforestation. The main milestones in the development of the Czech forest are summed up in Fig. 2.

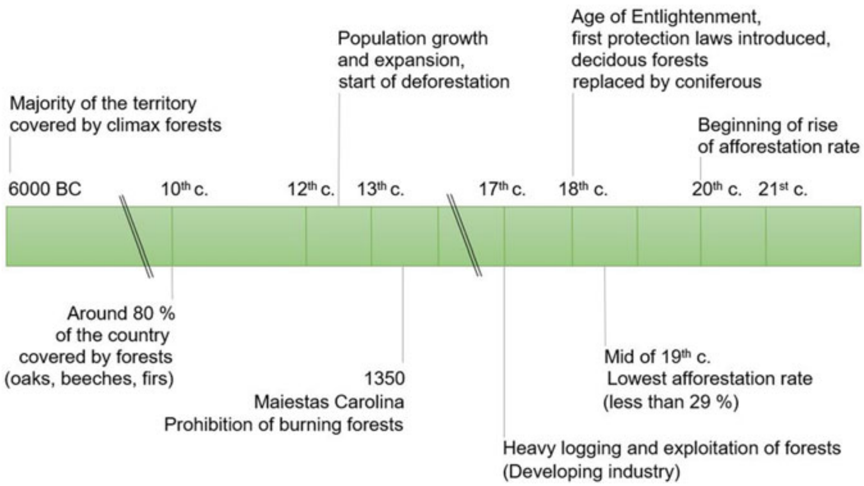

Fig. 2 Timeline of the main milestone in the history of the Czech forest. *c.–century

2 Forestry and the Current State of the Forest in the Czech Republic

Currently, forest covers more than one-third (36.8%) of the country (Kučera & Adolt, 2019). More than 70% are coniferous forests consisting of 50% *Picea abies*; 16% *Pinus sylvestris*; *Larix decidua*, and *Abies alb*a. 27% are deciduous species comprising mainly *Fagus Sylvatica* (9%) and *Quercus robur* (7%). The rest is composed of mixed forests. The distribution of coniferous forests varies in individual regions. Approximately 53.79% of forests of the CR are owned by the state from which 44.4% are possessed by the state-owned enterprise (SOE) Lesy ČR (Forest of the CR, SOE) and the difference is divided between military division (4.70%) and Ministry of the Environment (3.65%) (Ministry of Agriculture, 2021).

Forestry has been interwoven with wood processing since long centuries ago making wood production a forestry priority (Vyskot, 2003). These circumstances shaped the composition and structure of Czech forests and up to this day, one of the main priorities remains commercial wood production. Despite this fact, the ecological importance of forests was acknowledged and since 1986 forest health has been systematically monitored throughout the CR as a part of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (Forestry and Game Management Research Institute) . The consistent and coordinated monitoring of forest health at the European level was triggered by the sharp deterioration of forest health in European countries in the early 1980s which was a result of the long-term harmful effect of air pollution (Ministry of Agriculture, 2019). Notwithstanding the improvement of the air quality and related impact on the forest state, the Czech forestry sector has been experiencing a complicated situation in recent years. The main harmful factors can be divided into abiotic and biotic.

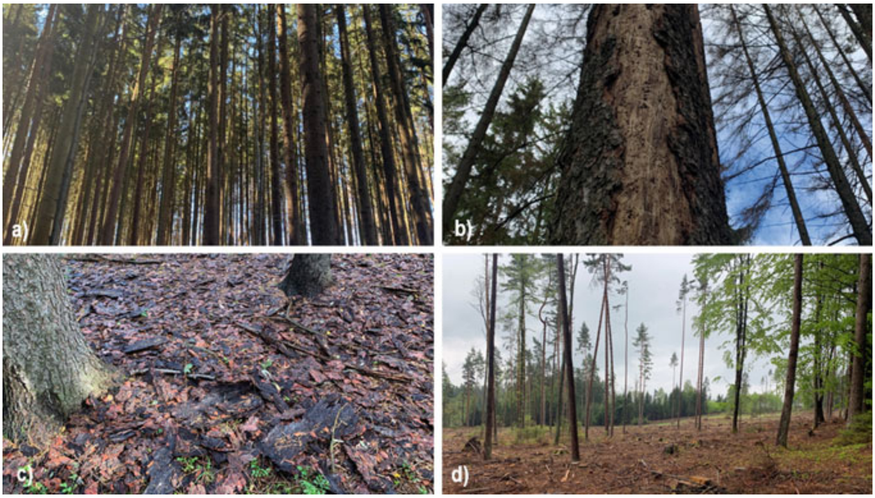

Fig. 3 Bark beetle infection in a spruce monoculture **a** monoculture of *Picea abies*; **b** a tree infested by bark beetle; **c** bark fallen off infested trees; **d** aftermath of bark beetle calamity

Abiotic factors were primarily the aftermath of storms and winds which had caused tree uprooting in large areas, and the drought. The biotic factors were presented by damage caused by the outbreak of bark beetle. The damage inflicted by biotic factors was substantially higher than by abiotic factors (Knížek & Liška, 2020). Since coniferous monocultures did not support ecosystem stability, the vitality of the Czech forest was debilitated within the whole country and the outbreak of bark beetle reached a calamity state in almost all the regions (Fig. 3).

3 Forest Fires and Their Incidence in the Czech Republic

The Fire and Rescue Service of the CR defines a forest fire as a fire in the natural environment. Namely, fires of forest cover, bush and dry grass that are uncontrolled, and freely spreading in mentioned settings. It is also a fire that breaks out in a forest and spreads in the forest and to other forest lands or breaks out in other lands and spreads into a forest and other forest lands (FRS of The Moravian-Silesian Region, 2022).

Firefighters in the CR consider forest fires as one of the most difficult kinds of fires to extinguish due to the large and often inaccessible areas fires can spread on, a potentially insufficient amount of water at the site of the fire, low bearing capacity of forest roads and the terrain, and possible abrupt change of climatic conditions (wind) (Francl, 2007). From a point of view of extinguishing fires, CR benefits from a densely fragmented landscape which is culturally managed and forests form usually smaller units. A rich network of forest paths and relatively populated rural areas also

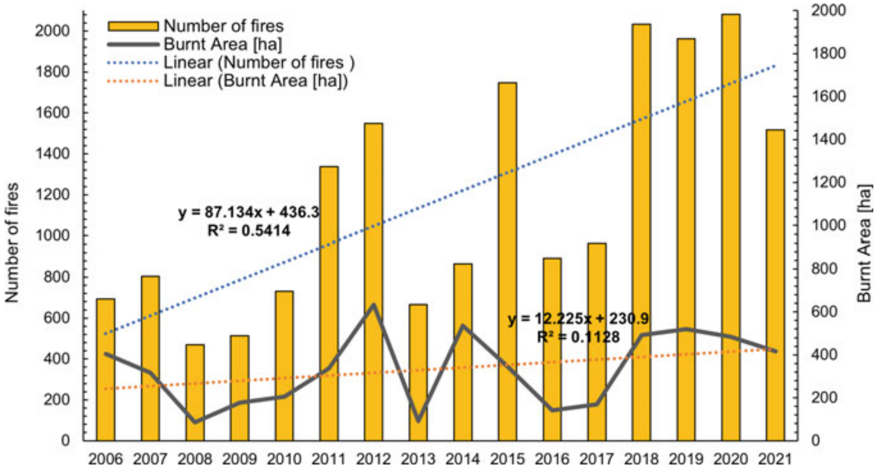

Fig. 4 Fire incidence and burnt areas during years 2006–2021 based on data from Statistical Annual Report by FRS CR 2012, 2021, Czech Republic, available: https://www.hzscr.cz/clanek/statisticke-rocenky-hasicskeho-zachranneho-sboru-cr.aspx

contribute to the timely detection of fires. Thanks to the above mentioned, forest fires do not usually reach catastrophic dimensions and consequences as in drier or more forested European countries. The average size of a burnt area during a forest fire is approximately 0.35 ha, but mostly smaller than 0.05 ha (Holuša et al., 2018). FRS officially started to record the data about wildfires in 2006; however, until 2011 the data must be taken with discretion as they varied among individual regions as far as fire locations logging is considered (Špulák, 2022). Figure 4 depicts fire incidence and burnt areas during the years 2006–2021. Both regression lines (blue line for the number of fires; red line for the burnt area) show an increasing trend.

The number of fires has a noticeably increasing tendency in the monitored years, which shows that the conditions for the occurrence of fires are more favorable. The causes of this trend can be found both in more frequent periods of drought, in the poor condition of forest vegetation, and the calamitous occurrence of bark beetle. Forest vegetation exposed to an unfavorable water regime, and also to pests, dies faster and biomass suitable for the creation and spread of fires accumulates in the forests.

The total burnt area grows considerably more slowly over the same period. It can be assumed that the slow increase of the total burnt area is currently being limited by the quick and efficient activity of the FRS CR. It is the speed and effective extinguishing of forest fires that can be decisive for a slower increase in the total burnt area. However, the capacity of the FRS CR is heavily exploited by the increasing number of fire incidents, and it may be only a matter of time before this capacity will be exhausted. The CR does not have recent experience with large-scale forest fires. The condition of the forests, changing climatic conditions and the workload of the FRS CR create hazardous conditions for the spread of this kind of forest fire.

Concerning devising forest fire preventive approaches, it is important to factor in that the incidence of forest fires in CR is not evenly distributed throughout individual regions. The collected data by FRS CR demonstrates that the number of fires in individual regions differs and is variable over time. In the long term, the highest absolute number of forest fires has been registered in Ústí Region, followed by the Central Bohemia and South Moravian Regions. However, the absolute number of fires does not provide comparable values; therefore, the conversion to relative numbers of fires is necessary and the absolute number must be recalculated per inhabitant. Even after the conversion, the Ústí Region remains the region with the highest annual number of fires but is followed by Karlovy Vary and Liberec regions (Špulák, 2022). These three regions are in the northern part of the CR and are specific by high afforestation and mountainous rugged terrain with difficult accessibility (Fig. 5).

Owing to the location and latitude of the CR and its geomorphological character, a large part of the country represents less fire-prone environmental zones (Trnka et al., 2021). The most common wildfires are surface fires. They account for more than 90% of all fires. There is less than 1% attributed to crown fires; however, their aftermath is usually enormous. Ground fires happen sporadically in the CR (less than 1%) (Holuša et al., 2018). The most frequent cause of wildfires in the CR is human carelessness proceeding from not complying with legislative or preventive regulations. Worth mentioning is smoking in the forest and discarding cigarette butts, disrespecting the ban on setting fires in the forest and their subsequent insufficient extinguishing or improper disposal of garbage (thrown glass, plastic film or metal) which can serve as an ignition trigger under certain circumstances (Francl, 2007).

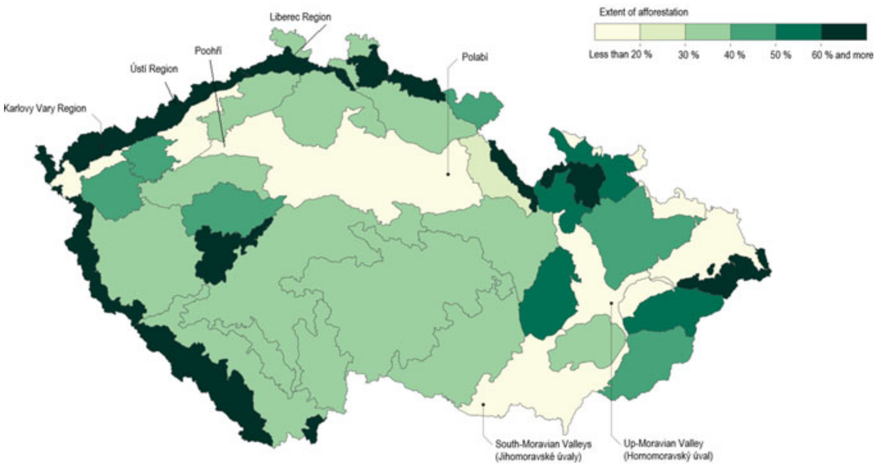

Fig. 5 Map of natural forest areas (NFA)–NFA is an area determined by the state and characterized by similar growth conditions for a forest, e.g., climate, soil composition, and terrain. *Source* The most recent research of the National Forest Inventory (2011–2015), published in 2019. (Lesnatost v přírodních lesních oblastech, 2022), available at: https://faktaoklimatu.cz/infografiky/lesnatost-plo

4 Legislative Framework Related to Forest Fires in the Czech Republic

The European Union (EU) does not have a unified policy for the forestry sector; therefore, the forest management and fire policy fall under the national competencies of individual member states (European Parliament, 2022). The area of wildfires is legislatively covered by 3 acts in the CR namely: Fire Prevention Act, Forest Act and Construction Act. While the Forest Act delimits activities that are forbidden in the forest, the Fire Prevention Act focuses on fire prevention, obligations of the natural and legal person and tasks assigned to state authorities (Holuša et al., 2018). The extinguishing of fires is covered by a strategical document Fire tactics issued by the Directorate of FRS CR (Pecl et al., 2021) and "Guidelines for aerial firefighting of the forest fires" which is an agreement between the Ministry of the Interior and the Ministry of the Agriculture (Špulák, 2019). The part of the Construction Act related to the forest fire can be seen in a figurative sense in granting permission to locate constructions and buildings on forest land or within a 50 m distance from the forest.

Various regulations are emerging from the mentioned laws that are not fully followed, or their compliance has not been checked for years. For this reason, many forest fires also damage property and endanger human lives. The prevention strategy should focus on compliance with legal regulations, i.e., checking the areas where buildings and constructions are located close to forests. During a recent forest fire in the National Park Czech Switzerland (located in Ústí Region) which took place in August 2022, several villages had to be evacuated because they were at immediate risk of fire due to their location near forested areas. This proves non-compliance with the regulation arising from the Construction Act on the location of buildings. From the historical photographs, it is evident that the surroundings did not use to be as forested as they are now. The area was not maintained for long years and so the environment changed into a high fire risk environment which was confirmed during the fire.

5 Executive Body—Fire and Rescue Service of the Czech Republic and Forest of the Czech Republic, a State-Owned Enterprise

In practice, it is the FRS CR that deals with extinguishing wildfires, and the State-Owned Enterprise Forest of the CR, SOE that focuses on forest fire prevention. FRS CR consists of 14 regional Fire and Rescue Services, including the Capital City of Prague Fire and Rescue Service. A major part of the resources appointed for fighting wildfires is organized on a regional basis as well (Špulák, 2019).

5.1 Fire and Rescue Service of the Czech Republic

Till 2013, the firefighting equipment was relatively obsolete with items dating back to 1970. The change started to occur after 2013 when FRS CR began to implement projects focused on the restoration and purchase of modern innovative technology designed to increase the quality of solutions during extraordinary events and natural disasters. These projects were co-financed by the EU up to 85%. A large amount of equipment was acquired (Horník, 2017). The most important for forest fire fighting were command cars, all-terrain vehicles, refueling containers for large-volume firefighting, armored vehicle for fire intervention in dangerous environments (with risk of explosion, natural fires) and thermal cameras. The firefighting equipment and resources are located throughout all the regions of the CR to guarantee the same quality, efficiency and timeliness of public services provided by the FRS CR to all the citizens in the CR (Horník, 2017). Securing fire protection on a territory of a municipality has historically been entrusted to the authority of the municipalities. Citizens were informed about the fire through a public announcement and were ordered to help extinguish the fire. Currently, the basic pillar of the system of Fire Protection Units coverage on a regional basis consists of regional fire rescue units, which are supplemented and supported to a significant extent by units of municipal volunteer fire brigades (Ministry of the Interior, 2014).

5.2 Forest of the Czech Republic, State-Owned Enterprise

Forest of the CR, a State-owned enterprise is concerned about the risk of forest fires. The situation has been intensified by climate phenomena and the bark beetle aftermath. Both factors resulted in altering microclimate conditions of many most affected areas where the space dries out easier and herbaceous layer accumulates due to overgrowing and so supports the spread of potential fires. The State-owned enterprise adopts the issue of forest fires comprehensively and employs both scientific and practical knowledge and experience. Scientific institutions and universities elaborated various certified methodologies. One formulates graduated adaptation and mitigation measures to reduce fire risk and the spread of fire in the landscape (Trnka et al., 2020) and devised an interactive application “Fire risk” which serves for detailed monitoring and prediction of risk of wildfires occurrence (Fig. 6). This tool uses Fire Weather Index (FWI) for prediction and is updated daily and it can be easily checked anytime publicly. FWI is used for the estimation of fire danger based on the calculation of a combination of meteorological conditions (FireRisk, 2022).

From a practical point of view, Forest of the CR, a State-owned enterprise focuses on optimizing collaboration with FRS CR to interchange and share information about the organizational structure of forests, maps of water source locations and forest paths usable in the event of a fire. It is also dedicated to a long-term project consisting of the ability of the landscape and forest to maintain and withhold water

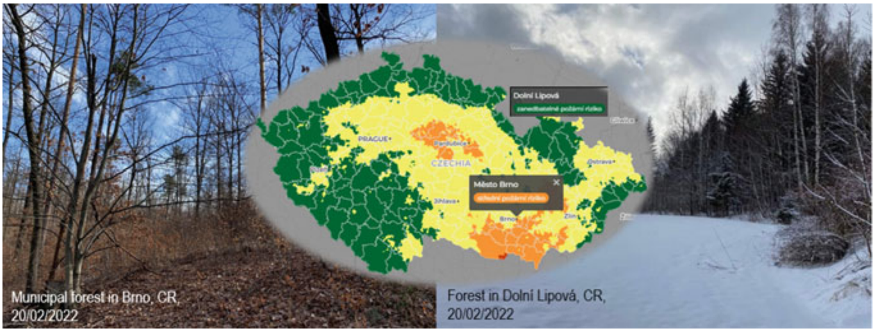

Fig. 6 Illustrative demonstration of Fire risk prediction on a specific day (February 20, 2022) in two places in the CR (Brno, Dolní Lipová). *Different colors represent the extent of fire risk (orange stands for medium fire risk and green for negligible fire risk)

through reconstruction, revitalization, and construction of streams, standing water bodies and other water structures (Smetana, 2020). Another equally important field is the enlightenment and education of the public, forest visitors and children through media campaigns, information boards in the forest, discussions and games in schools, etc. (Berčák et al., 2018).

Strategies, i.e., conceptual tasks, goals, measures and recommendations, are developed based on analyses of previous forest fires. Since a very common forest activity—burning brushwood—was identified as the riskiest factor in terms of fire hazard, related internal regulations were updated and clarified and certain measures such as the total prohibition of burning brushwood in the period from the beginning of April till the end of October, and the rules for the supervision and subsequent control of pile-burning places, were introduced (Smetana, 2020).

The prevention of the spread of fires is carried out by the detection patrol service provided by the Forest of the CR, SOE which involves both land and aerial patrols. Aerial patrols are fully paid for by the Ministry of Agriculture, and since 2018 they have been used only for extinguishing fires due to their high costs.

6 Conclusion and Challenges

The issue of forest fires in the CR is covered by several laws and related regulations, the FRS CR has strategic documents on fire tactics, and methods of extinguishing different types of forest fires. Still, it is really important to be aware that due to the changing climatic conditions, the general decline in soil moisture and the increasing number of fire-conducive days, the fire regime in the CR will change and the current approach will need to be adjusted to the new conditions and future trends. It is very advisable to seek knowledge and experience about firefighting in countries that face wildfires with higher frequency.

It is recommendable to invest in maintaining a high-quality technical basement because it is a determining factor for firefighting. Strengthening individual responsibility and applying high penalties for caused fires may lead to a more responsible behavior of forest visitors. The coronavirus pandemic has shown how effective media campaigns can be, and therefore this information channel should be used more for raising awareness about the issue of wildfires.

Newly established species-rich forests with uneven-aged structure will contribute to fire prevention because their species composition will be better adapted to the changing climatic conditions which imply that these ecosystems will feature higher stability. It is also necessary to aim at fuel management in the forests, improvement and reconstruction of forest paths, and the creation of firebreaks that prevent the fire spread and allow firefighters to capture a convenient firefighting spot.

Fires were part of the natural succession of vegetation and were a strong disturbance to the forest stands of Central Europe. Climax plant communities disturbed by fires allowed the vegetation to start a new successional series. The activity of human civilization blocks the succession of vegetation of current forests; therefore, a different reaction of current forest stands to fires can be assumed. The different composition of forests and climate change in Central Europe create new conditions for the occurrence, spread and dynamics of fires. Changes in the dynamics of fires and fire risk create and will create great pressure on the FRS, on forest management, and also on society as a whole. These changes will also create new conditions for the restoration of burnt areas and the regeneration of forest stands. The phenomenon of forest fires and post-fire recovery in the conditions of contemporary Central Europe brings many new questions and represents a great scientific challenge.

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Decision Systems in Disaster Management with Application to Fire

Maria Bostenaru Dan, Cerasella Crăciun, and Adrian Ibric

Abstract This book chapter explores the utilization of an ontology of disaster images in the design of a decision support system for intervening in prevention or reconstruction efforts following events such as earthquakes, floods, and even fires. Grounded in philosophy, ontology in computer science relies on taxonomies, which are classifications of concepts used to facilitate object-oriented programming. To this end, existing collections of disaster images have been analyzed based on relevant literature. The objective here is to map the perception of disasters across different groups, including experts, the passive public, and actively affected individuals. These stakeholders play a crucial role in decision-making within a participatory planning framework, with the most advanced form being strategic planning. This approach offers an alternative to traditional urban regulatory and landscape planning. Urban planning and land use are essential considerations for non-structural disaster prevention interventions, particularly in areas where urban and wildland environments intersect. In such contexts, the coexistence of human settlements and forests in urban settings emphasizes the dual nature of forests as both natural heritage and a domain that calls for nature-based solutions.

Keywords Urban planning · Heritage · Photography · Ontology · Digital humanities

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1 Introduction

The vulnerability of urban or rur-urban areas, particularly at the urban–rural border, should be closely linked to the fragility of the sensitive quasi-/semi-natural, anthropic/constructed, and cultural landscape. This connection becomes essential when researching and planning for complex hazards, which involve combinations of factors that can exponentially increase cumulative risks (Crăciun, 2014). In 2010, a grant from the Canadian Centre for Architecture (CCA) supported research into the photographic expressions found in the CCA's collection of images depicting earthquakes, floods, fires, and even armed conflicts (Bostenaru, 2011a). The project seeks to establish a fresh perspective on the CCA's collection images in this thematic context, following several years of research. Most of these photographs are now available in digital format. Consequently, these photographs serve as a means to preserve and capture the moment of catastrophe in a way that the physical ruins themselves cannot.

The Romantic Movement's penchant for depicting ruins in art brought a focus on nineteenth century photography of such events. This exploration drew from the archives of the Canadian Centre for Architecture in Montreal, Canada. It aimed to juxtapose the perspectives of the past with contemporary views on the same issues, leveraging digital tools to do so. The photographers who contributed to this collection are also documented in nineteenth century photography history books held by the CCA. The analysis utilized a range of works from the collection, including those by Hannavy (2007), Blau and Kaufman (1989), van Veen (2010), Klett (2006), (1871), Barnard (1872), Peabody et al. (1899), Palazzoli (1981), Taylor (2007), Harris (1993), as well as a later exhibition by Bigiotti and Corvino (2015) and the book by Birken (2018) on the topic.

Numerous authors have explored the role of nature-based solutions and land use (Butsic et al., 2015; Chas-Amil et al., 2012; Galliana-Martin, 2017; Hanberry, 2020; Monteiro & Tavares, 2015; Nickayin et al., 2020; Parker, 2020; Price & Bradstock, 2013) in wildfire hazard prevention at the urban–wildland interface as non-structural measures in disaster risk management (Gociman, 2000). This book chapter proposes classifying and mapping these solutions using photography to facilitate related decision-making. However, among international photographic collections, the CCA stands out as a unique resource, even when compared to institutions like the Getty Museum, research and conservation institutes of foundations (https://www.getty.edu/art/collection/search?size=48&view=grid&q=fire), or ICCROM (the "International Centre for the Study of the Preservation and Restoration of Cultural Property" in Rome), which house several national resources of photographic collections. These include foreign academies like the British School at Rome (https://digitalcollections.bsr.ac.uk/islandora/search/fire?type=dismax), where a course on the Glasgow Library fire was held on May 9, 2016 (https://www.gsa.ac.uk/life/gsa-events/events/r/rising-from-the-ashes/?source=filter&type=27676/mackintosh)—an event attended

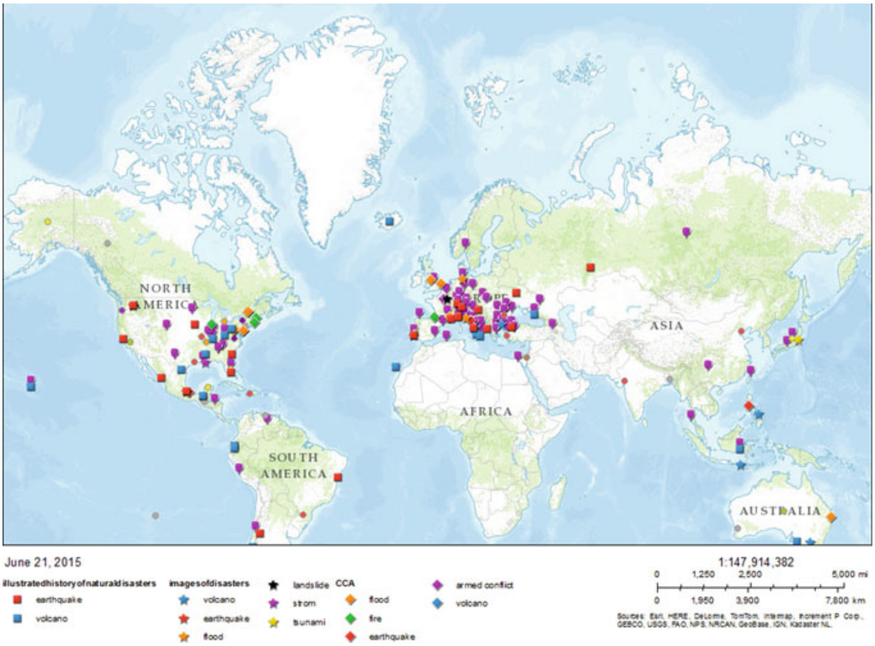


Fig. 1 Different hazards as mapped on the basis of the considered collections and databases (Bostenaru & Gociman, 2015)

by the first author. Other institutions, such as the American Academy in Rome (https://dhc.aarome.org/islandora/search/fire?type=dismax), and the collection at Bibliotheca Hertziana (https://foto.biblhertz.it/ete?action=queryFotos&desc=feuer+&refine=Suchen), have also contributed to the field. The CCA library's collection of books on the subject was also reviewed. An initial attempt to map these disasters is presented in Fig. 1.

The databases and collections included in Fig. 1 are as follows:

- The session series "Natural hazards' impact on urban areas and infrastructure," convened and co-convened by the first author over a period of 20 years at the European Geosciences General Assembly (1999–2000 convened by Friedemann Wenzel, 2001–2010 chaired and convened by the first author, see Bostenaru, 2011b). This series continued in 2023 after being co-convened by the first author as "Natural hazard impacts on technological systems and infrastructures" from 2013 to 2022 (for an overview, see session materials at https://meetingorganizer.copernicus.org/EGU2020/session/34881).
- Reviews of students supervised by the author as part of the course "Protection of settlements against risks" at the "Ion Mincu" University of Architecture and Urbanism. These reviews covered fires in the Mediterranean, Australia, and California and were presented at the COST action CA18135 webinar on May 5, 2021.

- A collection of historical photographs from the nineteenth century depicting various natural and man-made hazards, including fires (as shown in Table 1), sourced from the CCA.
- A collection derived from the exhibition and book on "Images of Disasters" (German research, Wieczorek et al., 2014), which includes major disasters throughout human history, providing an alternative to drawings through the use of photography.
- Another collection from one of the books, "Illustrated History of Natural Disasters" (Kozák & Černák, 2010), which covers major disasters from the dawn of civilization, similarly offering photographic representations.
- Additional works on architecture and catastrophes that were reviewed include "Tickle Your Catastrophe!" (Le Roy et al., 2011), based on the peer-reviewed proceedings of the conference with the same name held on March 6–7, 2009, in Ghent, Belgium. This conference included former CCA curator Dirk de Meyer.

A mapping of disasters is available as an app at http://www.arcgis.com/apps/Viewer/index.html?appid=6092a2d378404d6faab09b44a85f0aa2. This mapping draws a comparison between disasters mentioned in the CCA collection and those in various collections of disaster images, including books, exhibitions, or other visual data sources. This analysis is related to the examination of artistic photography using a method inspired by art historian René Berger (1963) for paintings and applied to cities by Kevin Lynch (1960). Berger's book primarily analyzes paintings, but the method, focused on understanding proportions and composition elements, can be applied to any type of image, including photographs. Lynch's work, on the other hand, mapped the perception of urban areas by categorizing elements of urban texture into landmarks, zones, paths, edges, and nodes. These categories are used to create mental maps when navigating a city.

Lynch's method has been adapted for landscapes by Popa (2014), making it suitable for aerial views, which constitute a significant portion of the images in the CCA collection. Popa (2014) views photography as a tool for preserving the memory and

Table 1 Fire events in the CCA collection

Known photographers who photographed such subjects	Individual events
J. Andrieu	Boston 1860, USA
Edouard Baldus	St. Claude, France
George N. Barnard	Paris (Commune), France
James Wallace Black	Philadelphia, USA
Robert Burley	Louisiana, USA
Alfred Capel-Cure	Notre Dame de Montréal, Canada
Franck	Chicago, USA
Frederick Gutekunst	Quebec, Canada
Brian Merrett	Illinois, USA
A. Richebourg	Portland (Maine), USA (stereo)
C. Seaver Jr	
John P. Soule	
William Notman & Son	

identity of landscapes, encompassing both natural and urban environments. This adaptability makes it suitable for analyzing urban landscapes affected by disasters, where visible changes are often documented in before-and-after photographs. Mental maps play a crucial role in risk perception, particularly in post-disaster reconstruction efforts, where preserving the heritage habitat (as defined by Gociman, 2000) is a priority. Another related mapping method from the 1950s, developed by Guy Debord (1955), laid the foundation for psycho-geography. This method is still used in contemporary urban analyses, including those within the COST action 18,126, in which the first author is involved. The upcoming steps in the analysis, as shown in Fig. 2, follow an ontology previously developed by the author (published in Bostenaru, 2011a) and are based on the elements of nature that cause disasters, as explained later.

2 Ontologies Review

Rehbein (2017) discusses the modeling of data in ontologies in a digital humanities textbook. Another approach by Timothy Tambassi (2018, 2021) establishes a connection between ontologies in philosophy and those in computer science. Within the domain of geo-ontologies, philosophical considerations related to mapping are explored. In the context of urban studies, the COST Transport and Urban Development Action C21, known as "Towntology—Urban Ontologies for Improved Communication in Urban Civil Engineering Projects," has addressed urban ontologies. Simultaneously, several ontologies have been developed for the field of architecture. An early effort by Sandaker (2010) focuses on the ontological representation of structures, a topic also relevant to disaster management given that structural failures are a primary cause of building collapses during disasters. This ontological approach was even integrated into doctoral courses, such as E-ArchiDoct's Virtual Campus on post-master Studies in Architecture, a collaborative project involving 14 European Schools of Architecture, including the university of the authors and the Oslo School of Architecture and Design. Sandaker presented related content during the "Structures and Architecture" conference in Guimaraes, Portugal, in July 2010.

Cacciotti et al. (2013) explored how monuments' documentation can be represented using ontologies. This approach extended to Building Information Modeling (BIM) and Heritage Building Information Modeling (H-BIM), addressing monument damage information modeling within a system. Tibaut et al. (2018) also investigated how collections can be transformed into databases using ontologies, focusing on heritage buildings but excluding the disaster dimension.

These ontological approaches primarily focus on data modeling for interventions in existing buildings. However, it is worth noting that ontologies can also be applied to new building projects, as demonstrated by Pauwels et al. (2009).

The first author has contributed to several ontologies in various contexts. In the COST TU0801 project, titled "Semantic Enrichment of 3D City Models for Sustainable Urban Development," different 3-D models were analyzed to find an

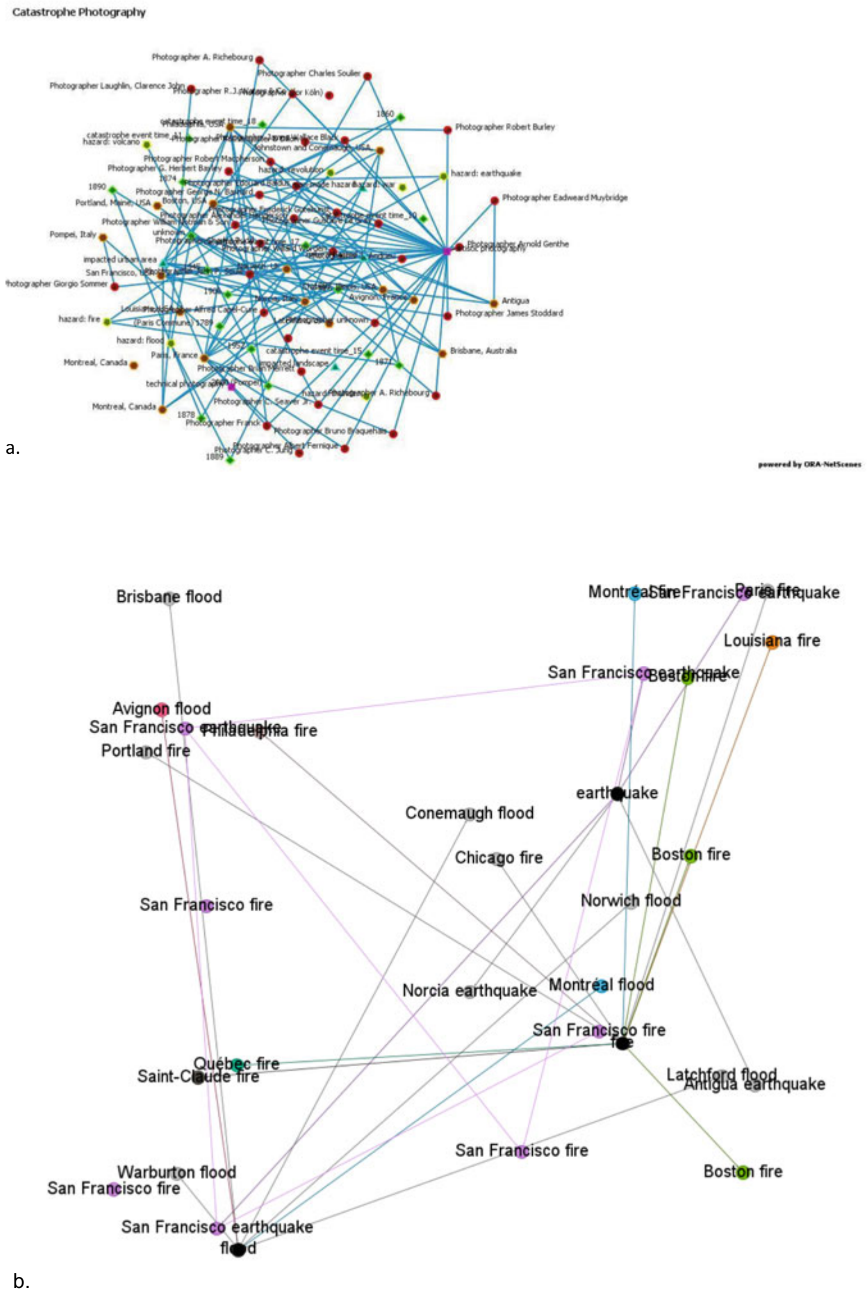


Fig. 2 Network analysis of nineteenth century disaster photography at the CCA **a** with ORA software (Bostenaru & Armas, 2015), **b** ordered with Gephi software

optimal solution for the city of Lisbon. Additionally, within the Network for Digital Methods in Arts and Humanities, a European Science Foundation research network, the NeDiMAH ontology working group was established, and the NeDiMAH Methods Ontology (http://nedimah.dcu.gr/) was developed.

In a recent COST network focused on Underground Built Heritage, the EU project HERACLES ontology (Hellmund et al., 2018), which addresses climate change disaster mitigation, was examined. An ontology was also created to organize disaster images (Bostenaru, 2011a). Furthermore, cost modeling for retrofitting in disaster prevention or post-disaster scenarios was centralized within VuWiki (Khazai et al., 2014), a Wiki platform for vulnerability information developed for the Global Earthquake Model socioeconomic component (https://storage.globalquakemodel.org/what/physical-integrated-risk/socio-economic-vulnerability/). Another contribution to the Global Earthquake Model involved the GEM Building Taxonomy Version 2.0 (https://www.globalquakemodel.org/single-post/2017/05/17/GEM-Building-Taxonomy-Version-20). This contribution entailed converting reports from the World Housing Encyclopedia initiative of the Earthquake Engineering Institute, which managed this component, into the taxonomy format. During this conversion process, the World Housing Encyclopedia's questionnaire was transformed into a taxonomy to serve as a foundational component for an ontology.

3 Results

Wildfires that affect urban areas are a critical subject within the broader field of vegetation fires, particularly forest fires. In English, they are commonly referred to as wildland fires in the wildland–urban interface (WUI). This interface represents the region where construction, especially residential development, is situated within or close to flammable vegetation. It is the area where wildfires pose the most significant risk to human populations, making it highly vulnerable due to the potential for human casualties. In many Central European countries, this specific topic has not received extensive research attention. While the risk in these regions is generally lower compared to Mediterranean countries, there are still areas that could be affected by wildfires, such as cities in Romania (e.g., Brașov, Piatra Neamț). Typically, these areas consist of clustered urban development with less interspersion with forests. Nevertheless, the potential risk exists and offers a valuable avenue for research (Lorenţ et al., 2018, 2022; Mallinis et al., 2019).

The National Institute for Research and Development in Forestry "Marin Drăcea" (INCDS) has included general protection measures against these fires in the Simplified Procedure conducted as part of The Romanian Operational Programme "Administrative Capacity," a structural instrument in forestry (SIPOCA 395 Project, 2021). This program, which implements the European Social Fund (ESF) during the 2014–2020 period, focuses on "The implementation and development of common systems and standards to optimize decision-making processes in the field of water and forests." It aims to apply an evidence-based approach to policymaking in the Ministry of Water and Forests and to systematize and simplify legislation related to water and reduce administrative burdens for businesses operating in the forestry sector. This program also addresses the interface area between the natural and built environment.

From an urban planning perspective, fires occurring at the urban–wildland interface impact the urban periphery. The Landscape Forum Le Notre dedicates a whole section to the urban periphery, and Stan (2013) discussed its current state. During the Modern Movement, the urban periphery gained special significance with the development of "Siedlungen," a German term referring to groups of small housing buildings located in the outskirts of cities. This approach not only introduced a new urban planning paradigm but also had implications for fire hazards. Unlike traditional urban blocks, the "Zeilenbau" concept emerged, characterized by the arrangement of long, narrow residential buildings perpendicular to the main street, each self-standing within green spaces. This layout had a different impact on the spread of fires due to the arrangement of buildings in relation to each other and to surrounding vegetation. While notable fires have affected individual buildings, including those from various architectural eras like the Middle Ages and Art Nouveau, urban fires capable of affecting entire areas, which can now be simulated thanks to increased computing power, can also be caused by wildfires. Urban and territorial strategies applied to landscape planning can effectively contribute to the resilience of complex integrated landscapes, encompassing quasi-/semi-natural, anthropic, and cultural elements. These landscapes can serve as both promoters and models for intervention strategies, representing a unique institutional form of urban and territorial management and planning (Crăciun, 2010).

Today, we are witnessing processes through which it is necessary to foresee possible "*Black Swan*" type events (Taleb, 2007) and to integrate vulnerabilities and the impact of the highly improbable, in the process of strategic planning of complex hazards, both at the European, regional, cross-border or territorial level, and at the local level of detail, on spatial urban design and landscape planning research, study, projects, and strategic regulations (Crăciun, 2021). The identification of areas with potential risk and the impact on the landscape and the urban life framework is necessary to be based on a specific methodology (Crăciun, 2009–2012, Fig. 3) of vulnerabilities to minimize the possible risks and identify the specific types of hazard and vulnerabilities relevant to the processes of territorial and urban development in landscape (Crăciun, 2013).

A decision ontology is building on these approaches with ontology for buildings in case of disasters (Fig. 4).

Papalou and Baros (2019), Mikkola (2008), and Papathoma-Köhle et al (2022) have provided valuable insights into how criteria weighting in decision trees can be performed. Papalou and Baros (2019) extend the common post-disaster rapid visual screening method, primarily used for earthquakes, to include fire hazards. They provide an example from a 2018 fire in Greece, assessing its impact on various building types, including concrete, masonry, timber, and steel skeleton structures. This approach, which considers structures based on their material composition, is a characteristic feature of the rapid visual screening method. Mikkola (2008) also

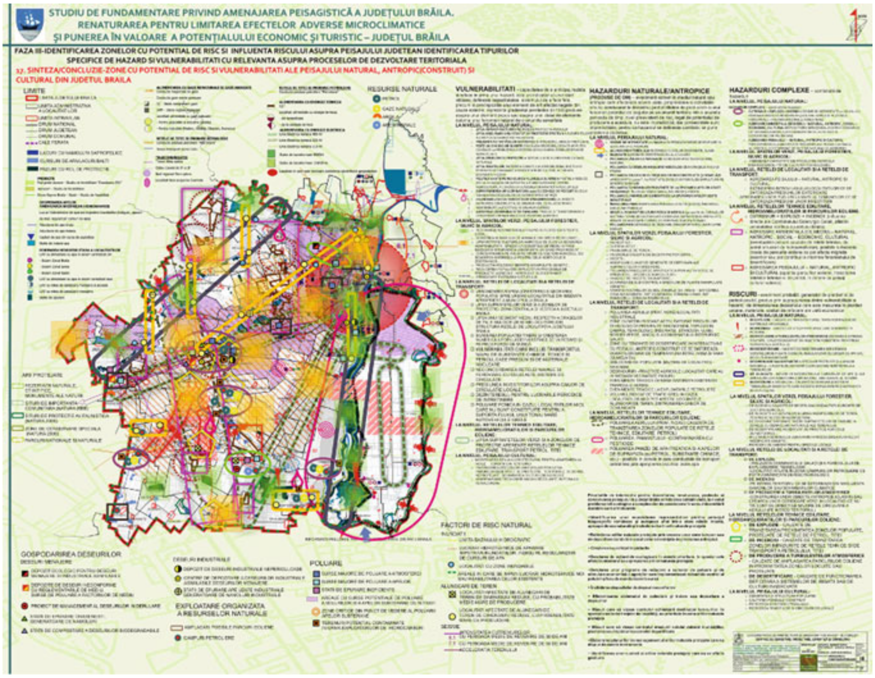
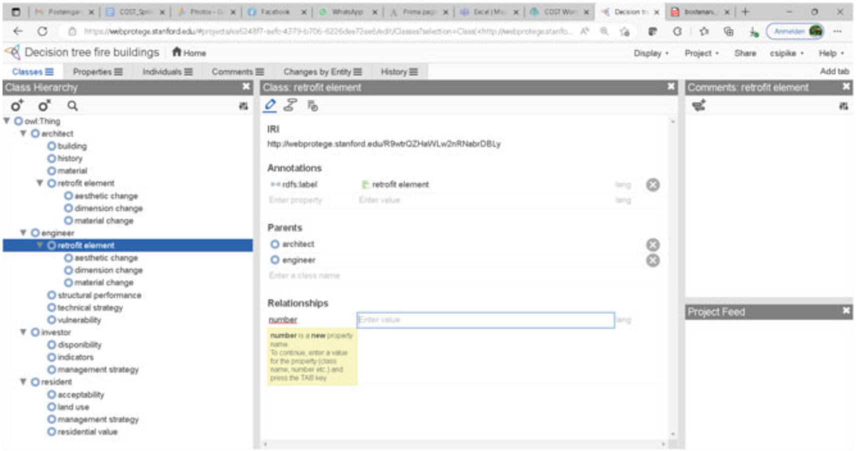


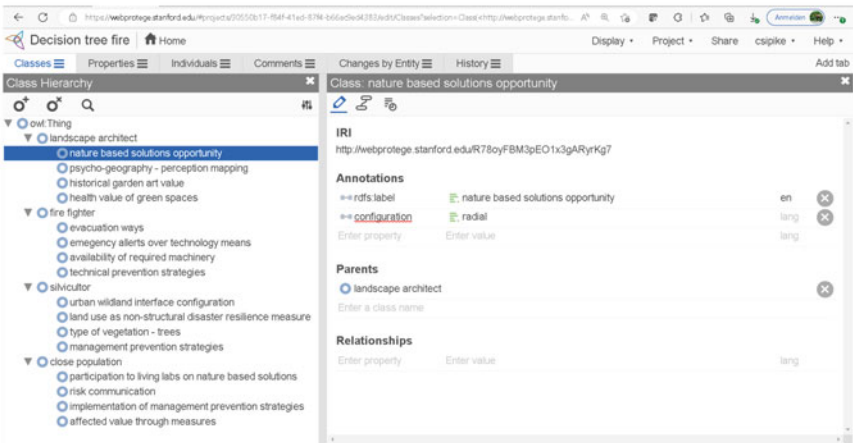
Fig. 3 Urban Territorial Masterplan nr. 17: Conclusions Synthesis—Areas with potential risk and vulnerabilities of the natural, anthropic/urban and cultural landscape in Brăila County, Romania, from research and applied case study project: New Methodological Integrate Complex Research of the Macro-and Mezzo-Scalar Level of the Natural, Anthropic and Cultural Landscape, Center for Research, Design, Expertise and Consulting of Bucharest "Ion Mincu" University of Architecture and Urbanism, Vol. III, pp.112–124 (*Source* Crăciun, Cerasella [2009–2012])

takes into account building materials but, prior to that, explores the effects of wildfires on buildings located at the urban–wildland interface. Drawing insights from a European project, this research not only examines how fires affect buildings and building materials but also investigates the mechanisms by which fires propagate toward buildings. It is worth noting that this research delves into impact assessment, a topic also covered in the mapped European Geosciences Union session. Additionally, the seminar works of students in the course have been included in the overview mapped in Fig. 1. Some of these presentations specifically focus on fires in the Mediterranean region, the USA (California), and Australia, aligning with the themes introduced by Papathoma-Köhle et al (2022).

Papathoma-Köhle et al (2022) emphasize the significance of the urban–wildland interface in the context of decision-making, aligning with the objective of this taxonomy. They also note that research on the vulnerability of the built environment to wildfires has been limited. To develop indices, they draw on a well-documented wildfire event, including one that occurred in Greece in 2018. Their approach differs from



a.



b.

Fig. 4 Decision ontology **a** multihazard ontology, **b** surroundings

the papers discussed earlier in that, in addition to structural type and building material—the literature review on physical vulnerability indexes also incorporates other factors like roof type. Moreover, they consider the relationship between buildings and their surroundings to assess the response of buildings to wildfires.

Figure 4b in our ontology primarily focuses on the surroundings, while rapid visual screening, as presented by Bektaş and Kegyes-Brassai (2022), is integrated into the multihazard ontology depicted in Fig. 4a. Future approaches should also consider interior furnishings, as highlighted in the discussion by Papathoma-Köhle et al (2022). Although we have partially addressed emergency response aspects in our work, they remain essential considerations.

Rapid visual screening can be adapted to different geographic regions based on architectural characteristics, as demonstrated in projects like Risk-UE for the Mediterranean region and Romania (Mouroux & Le Brun, 2008). Regarding the ontology section related to the building–surroundings relationship at the urban–wildland interface, we have developed weighting and indices, as required by the ontology. To determine these, we utilized the AHP MCDM method proposed by Saaty (1980). By categorizing vulnerability indicators into the two blocks, as also done by Papathoma-Köhle et al. (2022), our method covers a more extensive range of criteria—four times more. These criteria are grouped within the stakeholders' decision tree, streamlining the decision-making process. Ultimately, this decision-making process aids in retrofitting efforts, and some of the reviewed papers, including our method, can be instrumental in conducting cost–benefit analyses.

4 Conclusion and Final Remarks

We have examined the general approach to nineteenth century photography of disasters, encompassing urban photography series, stereo photography (as featured in scholars' selections), and the contemporary use of historic photographs in before-and-after comparisons. Numerous digital humanities centers house collections of catastrophe photographs, including those associated with foreign institutions in Rome, such as the Bibliotheca Hertziana, American Academy in Rome, and British School in Rome. The digital art history initiatives of the Getty Foundation have also sponsored courses on methods for working with images. Analyzing these images represents just one facet of a more comprehensive research project. As part of this project, the author intends to analyze their own images of endangered or resilient buildings using image analysis techniques such as mapping (including network mapping) and image annotation (using tools like ImagePlot, Netline, and Palladio). An ontology proves invaluable for categorizing images within a collection and organizing them into a database.

Increasingly, European projects are developing computer-supported decision systems to address climate change and the impact of other disasters on built and natural heritage. Recent examples include STORM, HERACLES, and ongoing projects like ARCH, SHELTER, and HYPERION, among others. In most cases, the starting point for designing these computer systems, often involving Internet of Things (IoT) approaches, is the ontology. In the author's project, the aim is to utilize images of monuments and sites from the first half of the twentieth century to draw lessons from vernacular architecture, which had a historically proven eco-adaptation. These lessons will inform the design of locally adapted retrofit solutions to mitigate hazards like wildfires in contemporary global contexts. During that period, the challenge was to build affordably and socially, leading to constructions in peripheral areas near forests. Today, environmental concerns drive change, with nature-based solutions being particularly relevant for addressing fire disasters, whether in urban settings adjacent to forests or in eco-architectural designs to protect materials from heat. This approach covers both aspects of the decision system we propose.

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Preliminary Assessment of the Wildfire Risks as a Tool for Their Management. The Case of Bulgarian Forests

Todor Stoyanov

Abstract The primary objective of this book chapter is to present an updated methodology for fire risk assessment, particularly in the context of Bulgarian forests. This update is essential due to the existing disparities among the tools and approaches used in previous assessments. The focus of this study is to develop a unified methodology for conducting preliminary risk assessments of wildfires, considering them as one of the most prevalent and natural disasters in forest ecosystems. The significance of such an updated methodology lies in the fact that different assessments can yield varying results for the same region, creating challenges for the development of sustainable land management plans and effective responses to potential wildfires. For instance, when using the approved national "Methodology for determining the risk of forest fires in the country" sanctioned by the Ministry of Agriculture, Food, and Forests (MAFF) of Bulgaria, which aligns with European requirements, some areas, like the territory of the State Forestry "Botevgrad" (TP SFE "Botevgrad"), were categorized as having a medium risk of wildfires. However, in the Forest Management Plan of TP SFE "Botevgrad," the degree of wildfire risk was classified as low. In light of these discrepancies, we have taken the initiative to enhance the methodology by including risk calculations for smaller units, such as subdivisions, sections, and enterprises. This approach seeks to provide a more accurate and detailed assessment of wildfire risk in specific forest areas.

Keywords Wildfire risk · Updated methodology · Fire hazard classes · Homogenization · Standardization

1 Introduction

Wildfires inflict substantial damage on forests and the forestry sector worldwide, with recent incidents in Europe highlighting the severity of the situation (Fernández-Anez et al., 2021). These fires generally have adverse effects on the economic, social,

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and environmental aspects of individual countries as well as the global ecosystem (Clarke et al., 2022). As a consequence of wildfires, substantial quantities of valuable timber are lost, and the condition of forest plantations is disrupted and deteriorated. Moreover, vast expanses of forested areas are deforested, compromising the protective functions of forests and diminishing their role in water protection. This leads to increased rates of soil erosion, particularly in mountainous regions.

According to wildfire statistics data (Stoyanov, 2021), the average annual area of burned forests in Bulgaria was 10,876 hectares during the period from 1995 to 2004. From 2005 to 2014, this figure decreased to 8,592 hectares, and between 2011 and 2020, it further reduced to 5,140 hectares. Despite the declining trend in the extent of wildfires in Bulgaria, they continue to pose a significant challenge and have substantial negative impacts on the state of forestry and the country's economy. As of 2021, Bulgarian forests cover 4,270,995 hectares, representing 38.7% of the total territory of the country, with the forested area accounting for 92% (Annual Report, 2021).

Forests in the Republic of Bulgaria can be categorized into different types, including state-owned forests (77.3%), municipal forests (11.2%), and those owned by public organizations, religious entities, or private individuals. Given this diversity, Assenova M. (2018) emphasized the importance of Geographic Information Systems (GIS) and the establishment of specialized databases to provide accurate data, relevant indicators, and updated maps. Such tools would facilitate the monitoring of wildfire risks, as well as the current and future forest conditions in Bulgaria. This, in turn, could enable the effective development of firefighting strategies and support the efforts of specialists across various sectors, including private enterprises, state forest management agencies, and their respective divisions and units.

2 Updating Methods and Standardization of Tools

The aim of this book chapter is to demonstrate how to update the existing methodology for assessing fire risks in Bulgarian forest areas, addressing the disparities among the tools previously employed. It's worth noting that such disparities are not unique to Bulgaria, and in this chapter, we will explore potential approaches to tackle this uncertainty. To achieve this objective, we will administer a risk factor questionnaire designed to describe and evaluate the current conditions within a specific study area. These risk factors will be ranked according to their severity, allowing for a comprehensive assessment of the risk of forest fires within each forest enterprise, as well as its individual sections. The area of forestry sections is further divided into divisions and subdivisions, representing the smallest territorial units within forest enterprises.

First, we utilized the "Methodology for determining the risk of forest fires in Bulgaria" (Lyubenov, 2016), followed by a combination of data derived from both national sources (Annual Reports for the years, 2009–2021) and European sources

("Forest Fires in Europe, 2002–2021") pertaining to forest fire statistics. Our intention is to propose a wildfire risk assessment methodology that not only ensures the accuracy of such assessments but also their practical applicability.

This approach is motivated by findings from "Determining the degree of risk of forest fires in TP SFE *Botevgrad*" (Stoyanov, 2021), which reveal that the approved methodology of the Forest Executive Agency (FEA) does not adequately account for wildfire risk at the levels of forest enterprises, sections, divisions, and subdivisions. Our scientific objective is grounded in the recognition that initial statistical information is often insufficient in terms of reliability and completeness. Additionally, certain information related to the fire hazard of forest areas is qualitative and cannot be quantified. Moreover, prolonging the data collection period can result in escalating evaluation costs. Furthermore, in the realm of researching complex systems and problems, including those encompassing fire safety, statistical information alone is often inadequate, necessitating the incorporation of specialized expert information, which includes normative and reference data. Models generated through the joint analysis of these two types of information are referred to as "Expert Statistical Models" (ESM).

In the context of addressing this problem, an Expert Statistical Model (ESM) should function as a mathematical representation of the relationship (function) between the level of fire hazard (safety), also known as the endogenous variable or output, and a vector of factors (exogenous variables or inputs) that influence it. The factors included in the questionnaire (checklist) and the descriptions of conditions are formulated such that responding "yes" always corresponds to 0, while responding "no" corresponds to 1. This formulation greatly simplifies the development of a software tool for automating the wildfire risk assessment process.

Wildfire risk, as defined, represents the mathematical expectation of the loss function's value. Its constituent elements include the probability of hazardous factors associated with wildfires affecting forests and the magnitude of resulting losses. Assessing the overall wildfire risk involves considering components such as fire occurrence, fire detection, fire progression, and fire suppression, including efforts to minimize the impact of hazardous factors. These components, in turn, are directly influenced by a range of organizational, technical, natural, and social factors.

3 Presentation of the Obtained Results for the Case of Bulgaria

In the initial stage, risks are assessed through expert evaluations to identify forest areas that require primary fire protection. Simultaneously, a preliminary risk assessment is conducted based on the most adverse (extreme) conditions and factors that could result in maximum risks. This assessment utilizes actual indicators observed on the day of the evaluation.

The integrated forest fire risk index (R_0) is determined by the formula:

$$R_0 = F(\overrightarrow{a}, \overrightarrow{x}) = \sum_{i=1}^{4} Bi(\sum_{j=1}^{k} A_{ij}a_j + \sum_{j=k+1}^{I} A_{ij}x_j \quad (1)$$

where:

$$\overline{a} = a1, \ldots, ak \quad (2)$$

– vector of uncontrollable parameters, expressing the quantitative values of various factors (natural, social, organizational, and technical);

$$\overline{x} = (xk + 1, \ldots, xl \quad (3)$$

– vector of controlled parameters, the values of which may change when planning a system of measures to reduce the risks of forest fires;
Bi—the coefficient of the significance of the i-th type of fire hazard in the integrated assessment ($i = 1, \ldots, 4$);
Aij—weighting factor, which takes into account the effect on the i-th type of fire hazard of the j-th parameter (uncontrolled—at $j = 1, \ldots, k$; controlled—at $j = k + 1, \ldots, l$).

Equation 1 is employed to calculate the integrated forest fire risk index, with the values achieved during the study being assigned to the controlled parameters. This proposed approach for determining forest fire risk can be characterized as a rapid method for risk assessment. Implementing this method will enable a practical evaluation of wildfire threats, identification of the most vulnerable forests, communities, and forested areas, and contribute to enhancing their fire protection measures.

3.1 Risk Assessment of Wildfire Factors

The process of assessing wildfire risks involves several key steps:

- Gathering information about the state of fire safety in forested areas, including reports, collected data, forest inventory records, fire safety plans, and other relevant documents.
- Evaluating the fire hazard within the region, taking into consideration factors such as the condition of forested areas, the presence of fire-prone sites, and the maintenance of forested lands.
- Assessing the effectiveness of measures implemented to ensure compliance with forest fire safety regulations, management practices, and other organizational and technical measures.
- This information is collected through a combination of surveys conducted by administrative personnel, forestry experts, and land tenants. It also involves

accessing statistical, technical, and forest inventory data, as well as conducting on-site inspections.

Subsequently, the gathered data is analyzed to derive both qualitative and quantitative insights into the wildfire risk levels. If the risk level is deemed acceptable, an action plan is developed, including prioritization of tasks and a timeline for future assessments. However, if the fire hazard is determined to be extremely high, immediate measures must be taken to enhance protection against forest fires.

3.2 Identification of Wildfire Risks

The assessment of wildfire risk involves identifying and evaluating all foreseeable and significant factors that could contribute to the occurrence of a wildfire. This includes an examination of potential sources of ignition and situations that may lead to wildfires. Figure 1 illustrates the primary conditions and factors that play a crucial role in determining the risk of forest fires.

Identifying and understanding these conditions and factors is essential for effectively assessing and managing the risk of wildfires in forested areas. By addressing these elements comprehensively, it becomes possible to implement measures to eliminate or control the various sources of fire risk, ultimately enhancing fire safety and protection of forested regions.

3.3 Assessment of the Factors in the Detection of a Wildfire

The risk of late detection of wildfires is influenced by various factors. Several elements can hinder the timely detection of fires, including atmospheric phenomena such as clouds, gas pollution, and smoke, as well as terrain features like high altitudes and steep inclines in hillslopes. Additionally, social factors play a role in detecting wildfires. The assistance of pedestrians, workers from different enterprises, and drivers (including those operating vehicles, river vessels, railways, aircraft, etc.) is crucial in identifying emerging fires and communicating this information to relevant fire department personnel.

The effectiveness of a forest fire detection system depends on a combination of organizational and technical factors. These factors include the presence of a territorial control system and the availability of means for transmitting operational information swiftly, all of which contribute to the overall efficiency of the wildfire detection and response efforts.

The wildfire probability detection function relies significantly on ground monitoring, which encompasses various components such as:

- Fire monitoring posts: These are strategically placed locations equipped for monitoring and detecting forest fires.

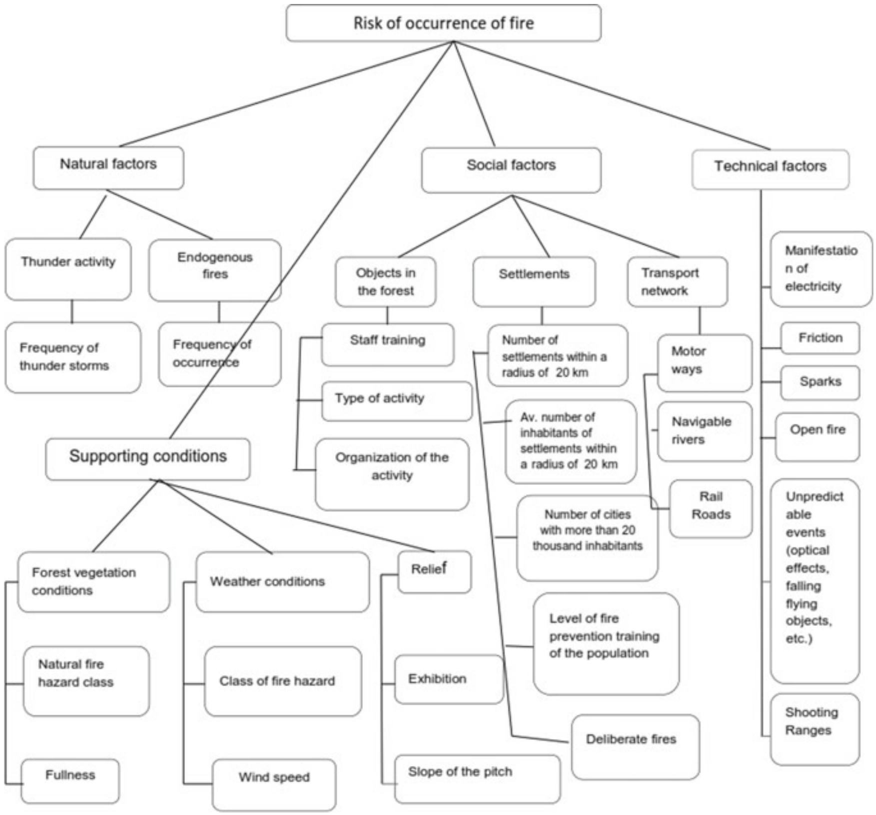

Fig. 1 Structural diagram of forest fire risk formation

- Lightning rods: Devices used to capture lightning strikes, as lightning is a common cause of forest fires.
- Television installations: These may include towers, antennas, and other communication equipment that can aid in the detection and reporting of fires.
- Patrolling: Regular patrolling of forested areas using various means, including drones, roads, motor transport, and river vessels, plays a crucial role in monitoring for potential fires.

To assess the probability of detecting a forest fire, coefficients are assigned to each of these factors to indicate their significance. These coefficients influence the overall assessment of the likelihood of detecting a forest fire based on whether these factors are present or absent during the survey of a specific area.

The structural diagram of how risk forms in the context of detecting a forest fire is illustrated in Fig. 2. Diagram providing an overview of the key conditions and factors that contribute to the risk associated with detecting forest fires.

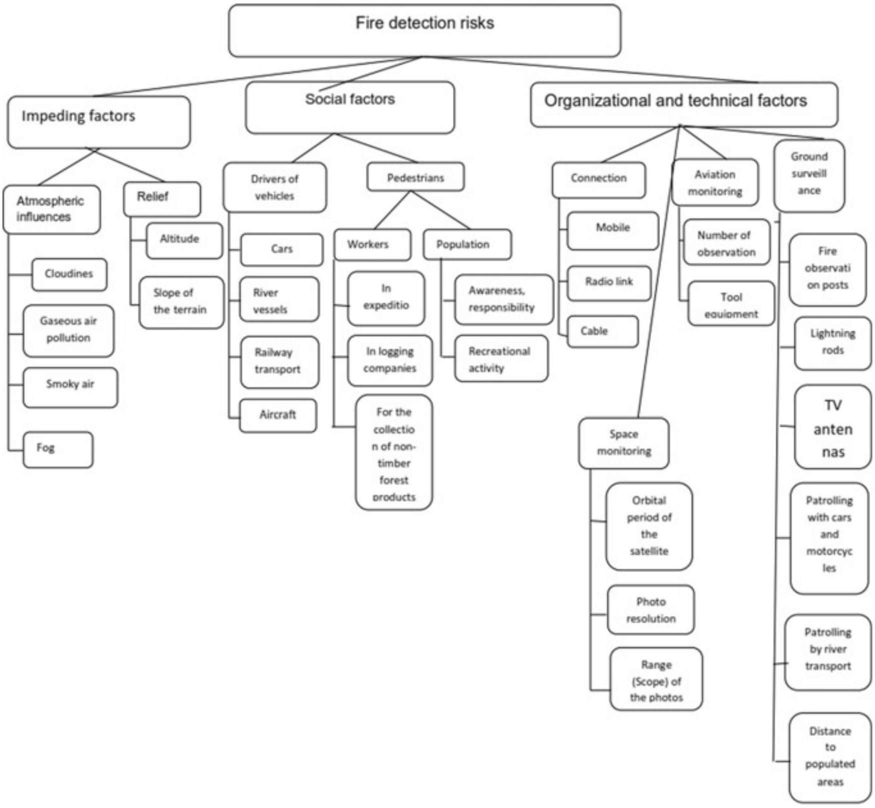

Fig. 2 Structural diagram of risk formation upon detection of a forest fire

3.4 Assessment of the Factors for the Development of Wildfires

When assessing the risk of forest fires, it's crucial to consider not only the possibility of ignition but also the potential for the fire to develop and spread uncontrollably. As a wildfire evolves, its risk level increases significantly. To account for this, the assessment of wildfire risk involves evaluating both the likelihood of a fire starting and the potential for it to escalate and become unmanageable. This comprehensive approach helps in better understanding and managing the risk associated with forest fires. Figure 3 outlines the main conditions and factors that contribute to the risk of forest fires, emphasizing the importance of considering both ignition and fire development in the risk assessment process.

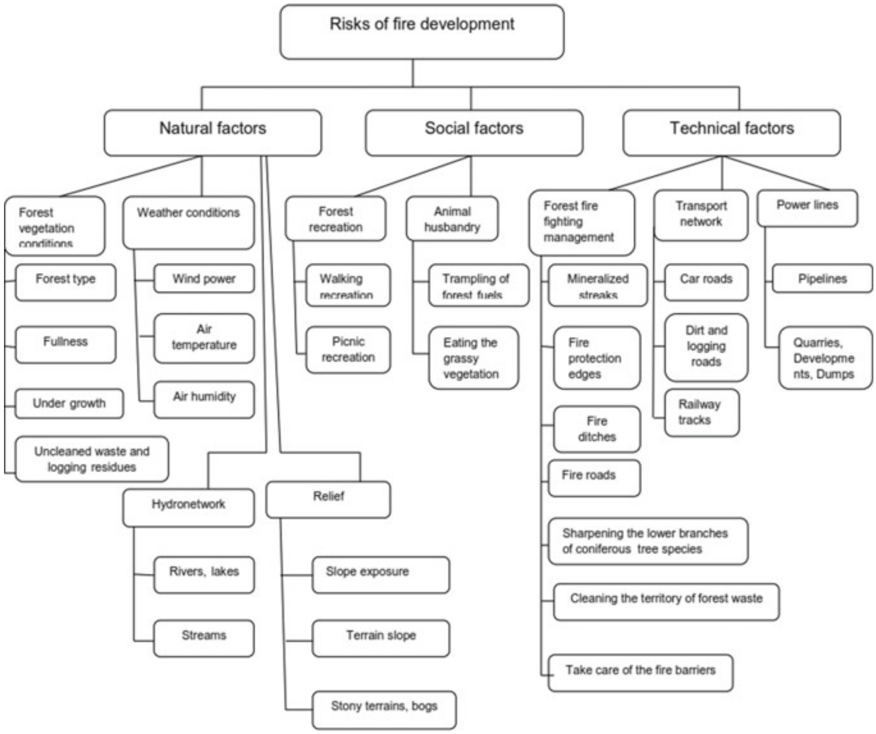

Fig. 3 Structural diagram of forest fire development risk formation

3.5 Assessment of the Factors for Extinguishing Wildfires

In the forest fire risk assessment process, the focus shifts to considering measures aimed at minimizing the consequences of emerging and spreading wildfires. This involves evaluating a combination of physical and organizational measures designed to combat wildfires effectively. Effective wildfire suppression depends on a range of factors falling into categories such as natural, social, technical, and organizational. These factors interact in complex ways to influence the ability to control and extinguish wildfires. Figure 4 illustrates the intricate structure of these key factors involved in wildfire suppression.

Implementing effective measures to protect forests from fires requires a collaborative approach involving various government departments and organizations. This includes cooperation with the Ministry of Interior, Ministry of Agriculture, Forest Executive Agency, departmental fire services, forest fire services, forestry and agricultural enterprises, and tenants. To facilitate this cooperation, it is recommended to establish a plan for interaction with these organizations. The effectiveness of wildfire suppression efforts is also influenced by the entity responsible for the assessed forest area, whether it is owned by the state, municipality, church, scientific organizations,

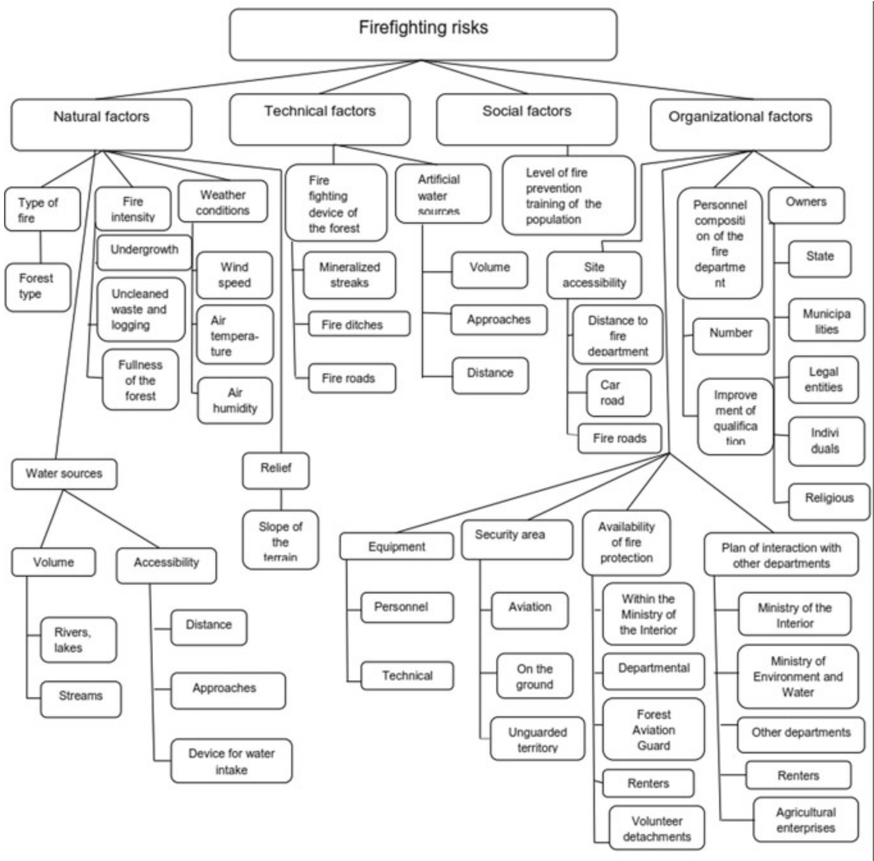

Fig. 4 Structural diagram of risk formation when extinguishing a forest fire

cooperatives, or other entities. Each of these entities may have varying capabilities and resources related to fire safety, making it essential to consider these factors in the assessment process.

3.6 Calculation and Formalization of Forest Fire Risk

The process of conducting a wildfire risk assessment involves several logical steps, with the questionnaire being a central component of this methodology. The developed questionnaire is designed to gather information and assess various factors related to the risk of wildfires. It aims to provide quantitative values for wildfire risk by combining probabilities associated with fire occurrence, development, detection, extinguishing, and the potential consequences of fires.

To ensure the accuracy of the assessment, it is essential to involve not only experts and survey results but also administrative staff, forestry specialists, and other relevant organizations. Additionally, available materials such as statistical data, maps, and forestry records should be utilized during the assessment process. The questionnaire consists of questions grouped by key factors, and each question is designed to produce quantitative or qualitative (yes/no) values that reflect the impact of each indicator. These values are then used for data processing and analysis to calculate the risks associated with fire occurrence, development, detection, extinguishing, and the overall integrated risk for a specific forest area, whether it be a division, subdivision, forest section, or forest enterprise. The risk of occurrence, late detection, development, and extinguishing risks—R_i) is determined by Eq. (4):

$$R_i = \sum_{i=1}^{k} A_{ij} a_j \tag{4}$$

where $\boldsymbol{a_i}$—quantitative (qualitative) values of various factors (natural, social, organizational and technical); $\boldsymbol{A_{ij}}$ is a weighting factor that takes into account the effect of the j-th parameter on the *i*-th type of fire hazard. The algorithm for calculating the *i*-th risk is (Eq. 5):

$$R_i = \left(r_0 = \sum KO_i KL_i\right) \rightarrow \left(r_i = \sum R_0 K2_i\right) \rightarrow \left(r_2 = \sum r_1 K3_i\right) \rightarrow \left(r_3 = \sum r_2 K4_i\right) \tag{5}$$

where r_i—intermediate values of risks of values, conditions, and factors. The total risk of fire is calculated by Eq. (6):

$$R_{tot} = \sum R_i K5_i \tag{6}$$

Then, the risks of forest occurrence of fires, development risks, detection, and extinguishing risks and the integrated (total) risk for forest division, subdivision, forest section, or forest enterprise are determined as weighted averages, taking into account the areas of these units and the total calculated area:

$$R_S = \frac{R1_{S1} + R2_{S2} + \cdots + Rn_{Sn}}{S} \tag{7}$$

where $\boldsymbol{R_s}$—risk (occurrence, development, detection, extinguishing, and integral) for forest subdivision, forest section or forest enterprise; $\boldsymbol{R_n}$—the similar risk of forest division, subdivision, forest section or forest enterprise; $\boldsymbol{s_n}$—an area of forest subdivision, forest section or forest enterprise, hectares; $\boldsymbol{S}$ is the total estimated area, hectares.

Depending on the obtained numerical indicators for the risks of wildfires, the range of their possible values is divided into several intervals, each of which corresponds

Table 1 Classification values of forest fire risk (FFR)

Level of forest fire risk	Safe	Allowable			Inadmissible (Inacceptable)
		Acceptable	Conditionally acceptable	Elevated	
Estimated value	< 0.1	0.1 < 0.5	0.5 < 0.65	0.65 < 0.78	0.78 < 1

to a certain level of risk according to the accepted world gradation of risks (fire, industrial, etc.). Based on the results of the assessment of the main types of risks of forest fires (occurrence, development of fire, late detection, and unsuccessful extinguishing) for the forest division, subdivision, forest section, or forest enterprise is determined integrated risk assessment of wildfires and the corresponding level (Table 1).

4 Conclusions

The forest fire risk assessment process concludes with the development of an action plan that includes recommendations for reducing the level of fire risk to a specific limit or maintaining it at an acceptable level. Even if the current level of fire danger is deemed acceptable, these recommendations can facilitate the use of more cost-effective measures for preventing and extinguishing forest fires. The presented methodology for assessing forest fire risk is designed to assist practitioners in accurately evaluating risk at the smallest territorial divisions within forestry, including forest enterprises, forest sections, forest divisions, and subdivisions. It can be easily implemented at various levels of forest management and can contribute to improved risk classification within forestry operations.

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Vulnerability to Wildfires and Peri-urban Areas: An Integrated Socioenvironmental Assessment

Vito Imbrenda, Rosa Coluzzi, Bogdana Nosova, Pavel Cudlin, Rosario Turco, Luca Salvati, and Maria Lanfredi

Abstract Assuming landscape transformations as a process fueling the local level of vulnerability to wildfires, this work investigates the spatial distribution of selected land-use classes for two years (1975 and 2018) in a metropolitan region of the Mediterranean basin (Athens, central Greece). Built-up settlements and cropland expanded moderately over time, facing a slight decline in forests and semi-natural areas. These changes resulted in the inherent growth in local vulnerability to wildfires estimated using a composite indicator, namely the Fire Risk (FR) index developed in the framework of the MEDALUS international research project financed by the European Commission. Crop mosaics and discontinuous settlements were the classes contributing the most to FR growth. The empirical findings of our work suggest how the conversion of fringe landscapes toward simplified (and, likely, low-quality)

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cropland and pasture land, as well as the inherent fragmentation of natural/semi-natural landscape patches, is detrimental to environmental quality, increasing the potential exposure to peri-urban fires.

Keywords Urban growth · Vegetation · Fire risk · Composite indicators · Greece

1 Introduction

Suburban landscapes include a variety of land-use types reflected in fragmented morphologies and heterogeneous functions (Antrop, 2004; Duvernoy et al., 2018). Recent landscape transformations determined new elements and landscape structures superimposed upon the traditional (urban–rural) landscape mosaics (Alberti, 2010; Allen, 2003; Coluzzi et al., 2022; Delfanti et al., 2016Mc Donnell et al., 1997). These phenomena may reduce the intrinsic environmental quality of entire districts, determining an increased fragility of habitats, especially when located in ecologically sensitive areas (Foster et al., 2003; Imbrenda et al., 2022a; Jim, 2004; Johnson, 2001; Nickayin et al., 2022; Salvati et al., 2008; Zambon et al., 2018).

Mediterranean metropolises were affected by intense landscape transformations at the fringe, thanks to the rapid expansion of settlements observed since the 1950s and following the post-war demographic boom (Carlucci et al., 2018; Salvati, 2014; Salvati & Carlucci, 2016). These trends determined (and sometimes consolidated) a land take causing an irreversible loss in soil resources and cultural/natural heritages (Antrop, 2004; Atmis et al., 2007; Bianchini et al., 2021; Catalàn et al., 2008; Chorianopoulos et al., 2010; De Marco et al., 2019; Economidou, 1993; Nickayin et al., 2021; Salvati et al., 2012a; Santarsiero et al., 2022). Urbanization of already natural land with olive groves, vineyards, annual crops or shrublands, pastures and woodlots was largely documented along the fringe of Mediterranean cities (Barbati et al., 2013; Biasi et al., 2015; Cecchini et al., 2019; Paul & Tonts, 2005; Salvati et al., 2013a, Simoniello et al., 2022).

Less knowledge is however available on how landscape elements evolve, creating new structures and original patterns of functions (Imbrenda et al., 2022b; Kosmas et al., 2016; Marull et al., 2009), that may impact environmental quality at large (Falcucci et al., 2007; Salvati & Zitti, 2007, 2009; Zambon et al., 2017). In such contexts, wildfires shape the ecological fragility of Mediterranean fringe landscapes determining environmental degradation (e.g., on sloping/rocky/arid land, see Kosmas et al., 2000a, 2000b; Simeonakis et al., 2007; Salvati & Bajocco, 2011; Pignatti et al., 2015; Santarsiero et al., 2020; Nolè et al., 2020; Samela et al., 2022). Based on these premises, we assume land-use change as exerting a negative impact on the ecological fragility of a given territory fueling the intrinsic vulnerability to wildfires, likely determined by, e.g., modifications in plant cover and vegetation composition (Bajocco et al., 2015, 2016; Fares et al., 2017; Smiraglia et al., 2015).

A complete survey of land-use changes over 43 years (1975–2018) allowed us to estimate the spatiotemporal variation in a composite index of vulnerability to wildfires in a metropolitan region of Southern Europe (Athens, Greece) experiencing comparatively high exposure to fires than other metropolises in the macro-region, thus representing a sort of 'worst scenario' for other socioeconomic contexts in the same European quadrant. The explicit knowledge stemming from our study may support strategic planning containing wildfires and mitigating soil degradation and habitat fragmentation along urban fringes.

2 Methodology

The investigated area covers more than 3000 km^2, a large part of the administrative region of Attica, Central Greece (Fig. 1). The area was partitioned into 115 mainland municipalities (58 forming Athens' conurbation that extends 430 km^2), including two municipalities on Salamina island close to Piraeus harbor, and excluding the remaining municipalities in the other islands of Argosaronic Gulf, Aegean Sea. The area consists of mountains with the highest elevation in Mount Parnitha, 25 km far away from downtown Athens (1413 m on the sea level). Three coastal plains (Messoghia, Marathon and Thriasio) are located immediately outside Athens' conurbation (Ciommi et al., 2019; Di Feliciantonio et al., 2018; Salvati et al., 2012b, 2013b). The population living in the area amounted to 1.6 million people in 1951, increasing to 2.7 million people in 1971 (approximately 900 inhabitants/km^2) and reaching 3.7 million people in 2021 (nearly 1200 inhabitants/km^2). Urban population in total population declined from the peak of 92% observed in 1971 to 80% in 2021 (Gavalas et al., 2014).

The spatial distribution of selected land-use classes was investigated over two years (1975 and 2018) based on (i) the LaCoast (LC) digital cartography available for 1975 at 1:100,000 scale and covering the European coastal areas (Perdigao and Christiansen, 2000) and (ii) the Corine Land Cover (CLC) pan-European digital cartography available at the same spatial scale for 2018 (Büttner et al., 2017).

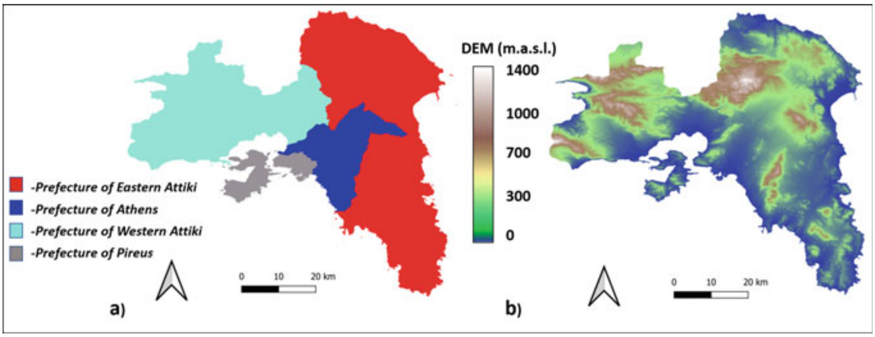

Fig. 1 Study area of Attica (Greece): **a** location of four prefectures and **b** Digital Elevation Model from EU-DEM dataset

These two geospatial sources were regarded as comparable digital maps covering the study area homogeneously in the two-time points, in line with the nomenclature of the CLC project. Being coordinated by the European Environmental Agency (EEA), this initiative provided land-use maps multiple times for the whole of Europe with an inventory based on satellite images as the primary information source, with spatial scale (1:100.000), geometric resolution (minimum mapping unit of 25 ha), and minimum width of linear elements (100 m) reflecting the trade-off between production costs and level of detail of land cover information. By providing a comprehensive description of the landscape in the study area (Economidou, 1993), the standard CLC nomenclature includes 44 land classes (Salvati & Bajocco, 2011) grouped into a three-level hierarchy (1: artificial surfaces, 2: agricultural areas, 3: forests and semi-natural areas, 4: wetlands, and 5: water bodies).

The vulnerability of plant cover to fires was derived, composing the information from the two maps described above following the rules dictated by a quantitative approach developed in the Environmentally Sensitive Area (ESA) methodology of the Medalus II (Mediterranean Desertification and Land Use) international cooperative research project (Kosmas et al., 1999). Being explicitly validated on the field in several target sites (Brandt, 2005), this framework was applied at both the regional and local scale in Mediterranean regions displaying locally differentiated environmental conditions (Imbrenda et al., 2021; Lanfredi et al., 2022; Pace et al., 2023).

Vegetation vulnerability to fires was estimated by attributing a score between 1 and 2 to each land-use class and leading to a final indicator named FR ('Fire Risk': Salvati & Bajocco, 2011). The approach was supported by a preliminary analysis (Kosmas et al., 2000a) developed to define the correlation between each land-use type and fire vulnerability based on literature review and field research mostly collected in the framework of Medalus projects (e.g., Basso et al., 2000; Brandt, 2005; Kosmas et al., 2000b). The results of a sensitivity analysis and a focus group allow for confirming the most valid, low-cost, and efficient score set (Kosmas et al., 1999). Ranging from 1 (the lowest vulnerability to wildfires) to 2 (the highest vulnerability to wildfires), FR indicated zero values assigned to land-use classes that were excluded from the analysis, namely compact urbanization (Salvati & Zitti, 2012).

The spatial distribution of the FR index was mapped for 1975 and 2018 using the same spatial resolution of CLC maps. Land changes and the related variations in FR were studied at the first CLC-class level. This analysis gave information on the positive (or negative) contribution of each class to FR. Changes over time (1975–2018) in the average FR score were quantified separately for each municipality of the study area ($n = 115$) by using the 'intersect' tool provided with ArcGIS software (ESRI Inc., Redwoods, USA) after the overlap between the FR map in 1975 (or 2018) and the shapefile depicting the municipality's boundaries.

Table 1 Surface area of selected land-use classes in metropolitan Athens by year, and the consequent variation in the FR index

Class	1975	2018	% change in land cover*	% change in FR*
Built-up areas	15.6	16.9	0.9	0.75
Cropland	32.6	34.4	0.1	0.34
Forests/semi-natural areas	51.7	48.6	−0.3	−0.19

*Annual rate of change observed between 1975 and 2018

3 Results

Basic land-use changes between 1975 and 2018 were delineated in Table 1 and indicate that built-up areas and cropland expanded into other lands, although with different rates of increase, whereas forest/semi-natural landscape matrices decreased slightly. These changes resulted in a global rise of the FR index (0.1% per year – from 1.42 in 1975 to 1.44 in 2018). 'Complex cultivation patterns' contributed the most to the increase of the FR index (4.3% more than the average increase); 'land principally occupied by agriculture, with significant areas of natural vegetation' was the second contributor (2.0%). The highest negative contribution to FR came from 'sparsely vegetated areas' (−3.4%), 'olive groves' (−3.1%) and 'mixed woodlands' (−2.5%). At the aggregate level, however, urbanization (e.g., discontinuous, low-density settlements) contributed to FR more (0.75%) than cropland (+0.3%).

The spatial distribution of the FR index in 2018 was illustrated in Fig. 2. The districts with a high vulnerability to wildfires are concentrated in the Athens fringe. At large, plant cover vulnerability does not seem correlated with the distance from downtown Athens (Spearman rank correlation test, $p > 0.05$). Changes in the FR index along the 43 observation years were mapped at the municipal scale (Fig. 3). The increase in the FR index was spatially heterogeneous, concentrating in suburban municipalities North and East of Athens; these areas experienced low-density urban expansion. Few municipalities at the fringe also showed a moderate reduction in the FR index over time possibly due to the loss in forest cover caused by recurrent fire events in the last decades.

4 Discussion

Transforming fringe landscapes into low-quality cropland and fragmented forest mosaics is detrimental to environmental quality, exalting the ecological fragility of land (Corona, 2018; Corona et al., 2016; Nocentini et al., 2017; Recanatesi et al., 2016). As a possible response to urban sprawl, a rising vulnerability to wildfires was recorded in Attica, although with a mostly heterogeneous spatial pattern that suggests how suburbs between 15 and 30 km from downtown Athens are mostly endangered. Results also support the relevance of an ecological spiral of human

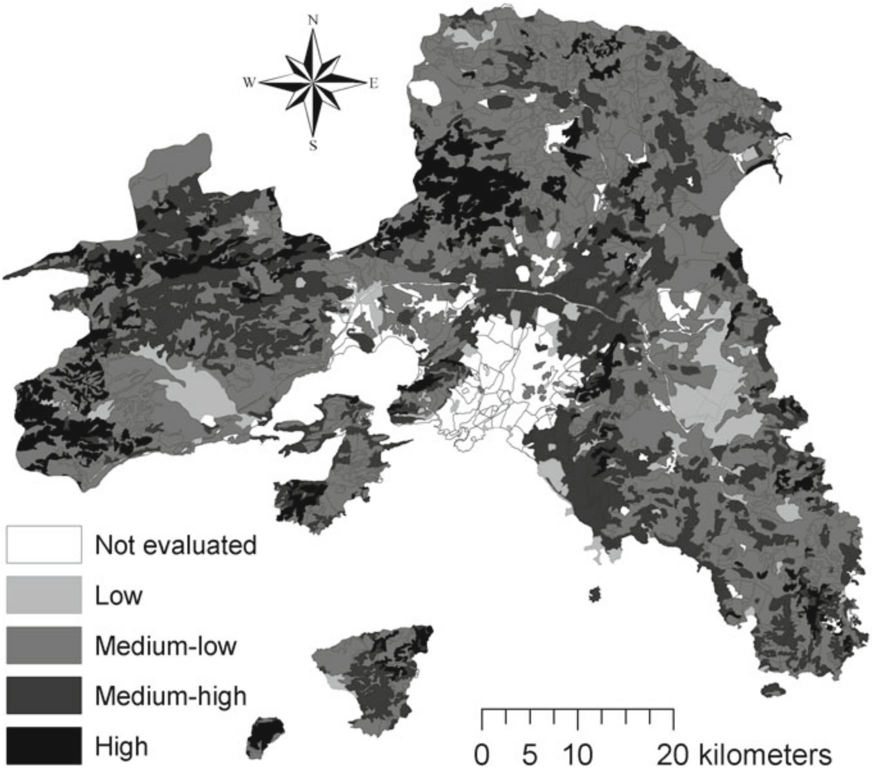

Fig. 2 Spatial distribution of Fire Risk index in the study area (2018)

pressure resulting in the increase of local vulnerability to wildfires. The recurrent fires in Attica (Salvati et al., 2012a, 2012b) have likely represented an additional engine of land-use changes. Coupled with the increasing events of droughts and the asynchronous distribution of rainfall across large areas (Coluzzi et al., 2020; Lanfredi et al., 2020), the synergistic impact of wildfires and landscape transformations have consolidated the local vulnerability to wildfires (Cillis et al., 2022; Salvati et al., 2013a, 2013b).

These trends can be assessed continuously by integrating remote sensing, geospatial information sources (e.g., Corine Land Cover maps), and field surveys estimating the environmental impact of urban sprawl (European Environment Agency, 2016). Altering landscape patterns and fragmenting high-quality vegetation covers, urban sprawl fueled the intrinsic divergence in 'extensive' and 'intensive' land uses, exacerbating the spatial polarization in high- and low-quality vegetation areas and thus increasing the local vulnerability of vegetation cover to wildfires (Pickett et al., 2001). The increase of vegetation vulnerability to fires because of inherent homogenization in species composition, disruption of the hydrological systems, and modification of

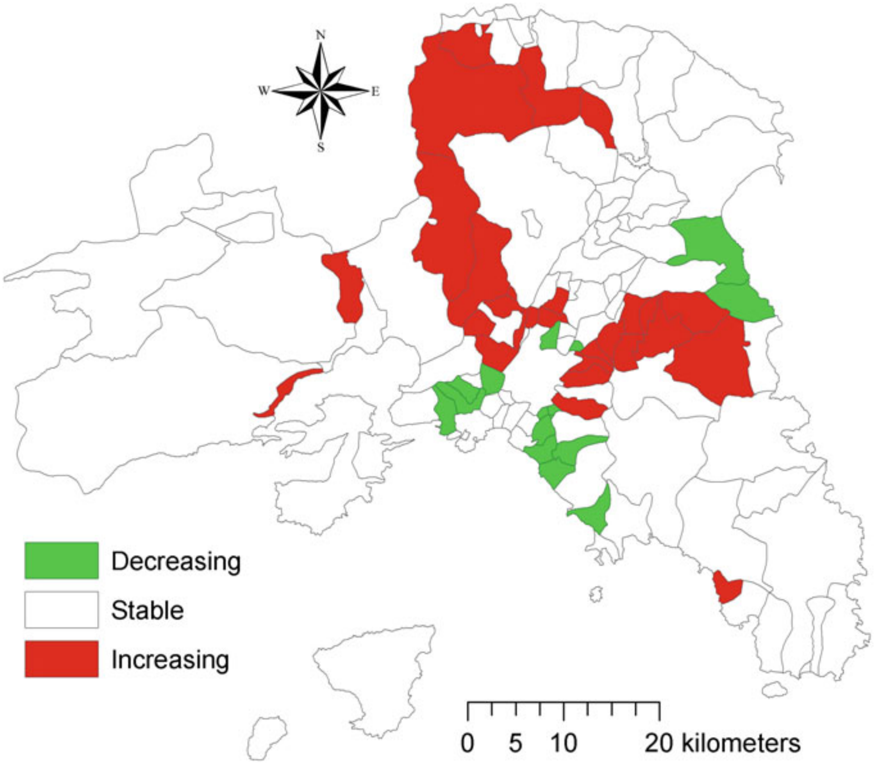

Fig. 3 Discretized changes over time in FR index in the municipalities belonging to metropolitan Athens between 1975 and 2018

energy flow and nutrient cycling (e.g., Alberti, 2010; Foster et al., 2003; Johnson, 2001) should be also monitored extensively in the framework discussed in our work.

5 Concluding Remarks

Sustainable land management in fringe districts is made more urgent with climate change and requires appropriate assessment methodologies and conservation strategies focusing on relict, high-quality vegetation cover (Chelleri et al., 2015; Ciommi et al., 2018; Perrin et al., 2018). Efforts are finally needed to effectively integrate ecological studies and socioeconomic disciplines in a comparative, local-scale perspective informing fire science and the prevention/suppression cycle in suburban areas.

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Wildland Firefighters: A Crucial Weapon for Forest Fire Management. Which Health Risks Do They Face?

Filipa Esteves, Joana Madureira, João Paulo Teixeira, and Solange Costa

Abstract Fire when uncontrolled can become a destructive force that risks wildlife, property, and human lives. Global warming has contributed to the increase and severity of wildfires in the last decades, requiring greater political and local authority involvement to protect people. Wildland firefighters are an essential tool for the management of any forest fire. However, they face unique occupational risks characterized by physically demanding tasks, long hours in severe conditions, and exposure to various health risks (e.g., burning, fractures, smoke inhalation), including exposure to carcinogenic pollutants emitted from smoke. These pollutants, including particulate matter, carbon monoxide, nitrogen dioxide, and volatile organic compounds, can cause acute adverse health effects but also long-term effects, such as cancer. Yet, evidence linking wildland firefighters' occupational exposure and health outcomes is limited. The increasing risk of wildfire occurrences and longer fire seasons highlight the need for occupational studies among these professionals commonly exposed to hazardous pollutants. Scientific evidence has contributed to the establishment of measures related to firefighters' health promotion. Regular monitoring, surveillance and health promotion activities, innovative firefighting techniques, safer personal protective equipment, and the implementation of written policies and procedures, such as decontaminating fire station equipment and spaces, are crucial to reduce firefighters' adverse health effects.

Keywords Wildland firefighters · Wildland fires · Climate change · Occupational exposure · Health risks · Air pollutants · Decontamination procedures

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1 Wildland Fires: Dealing with a New Era

Fire has always played an important role in shaping ecosystems constituting an essential component of ecological balance (Bond et al., 2005). It may be a useful tool, but, if untamed, may have a severe impact on wildlife habitats, goods, and people's lives. A "wildfire," "forest fire," "bushfire," "wildland fire," or "rural fire" (the term varies within countries) can be defined as an unplanned, uncontrolled, and unpredictable fire event that occurs in nature (Šomšák et al., 2009; CIFFC Glossary Task, and Training Working Group, 2017). The inevitability of global warming, with decreasing precipitation levels and prolonged dry seasons (Esteves et al., 2022a), has contributed to the increase in the number and severity of wildland fires (San-Miguel-Ayanz et al., 2018; Westerling et al., 2006).

As pointed out by the United Nations Intergovernmental Panel on Climate Change, there is a "*greater likelihood of injury, disease, and death due to more intense heat waves and fires*" (Field & Barros, 2014). Furthermore, the rising number of people working and/or living in areas close to forests increases the risk of serious damage to livelihoods or loss of human lives (Hirschberger, 2016; Radeloff et al., 2005). Thus, the more we know about wildfires' impact (e.g., effects on human health, millions lost to the economy, destroyed habitats, air pollution, burnt houses, loss of human lives), the more we must act on, concentrating efforts on prevention and fire response for a balanced and effective forest fire management.

The management of a forest fire per se lay mostly on the intervention of firefighters. In fact, wildland firefighters are considered the backbone for resolving any forest fire occurrence (Beighley & Hyde, 2018; Moreira et al., 2009). Having well-trained and healthy firefighters is crucial for an effective fire response. The predicted increase in wildland fires requires additional efforts from the workforce, and firefighters (Withen, 2015). Although firefighter is considered one of the most dangerous occupations in the world, little is known about the health risks related to their occupational exposure.

2 Wildland Firefighters: A Brief Contextualization

The first fire brigade, called "Vigiles," was created in 24 B.C. under the rule of Imperator Augustus and consisted of approximately 600 enslaved people and conscripts that patrolled the streets of Rome checking for crimes and fires (Butgereit et al., 2014). Later, in 60 A.D., imperator Nero allocated 7.000 freemen to fire prevention, firefighting, and building inspection activities (International Association of Fire Chiefs, 2008). After the Great Fire of London (1666) that destroyed nearly 80% of the city, insurance companies formed the first private fire brigades (Alagna, 2003). Over the centuries, firefighting systems were adjusted according to the reality of each country/people and their respective needs.

Currently, there are around 16 million firefighters in the world (91% males and 9% females) mostly volunteers, with the exception of a few countries (e.g., Italy, Spain, USA, Canada, France, Greece, Israel, and Singapore) (CTIF, 2022). Fire departments may be composed of either professional firefighters (full-time firefighters), volunteer firefighters, or both; in the United States (USA), for example, most fire departments consist of volunteer firefighters (International Association of Fire Chiefs, 2008). Generally, each fire department is responsible for a geographic area guaranteeing a fast response time (International Association of Fire Chiefs, 2008).

The risks posed by wildland firefighting are different from those related to any other type of fire suppression context (e.g., structural firefighting, such as urban). Wildland firefighters may participate in several wildfire occurrences per year and remain on the fire scene for several days/weeks (for multiple shifts with little downtime) in very hostile and unpredictable conditions (Demers et al., 2022).

Wildland firefighters have an enormous physical and psychological workload (Ruby et al., 2002); common tasks include trekking, chainsaw work, and brush removal (IARC, 2010) while carrying a considerable number of heavy equipment and tools (e.g., rakes, axes, shovels, fire hoses) (IARC, 2010; Smith et al., 2001) through remote and difficult terrains. In addition, wildland firefighters face high temperatures, high levels of noise (e.g., sirens, diesel engines) (Broyles et al., 2017), and high levels of stress, particularly when they confront life-risk situations or when they need to deal with injuries or fatalities (Smith et al., 2001). Often beginning at very young ages, most firefighters remain their entire lives in the force, being continually and repeatedly exposed to different hazards including carcinogenic air pollutants (Magnusson & Hultman, 2015). To reduce or restrict their occupational exposure, firefighters are required to use personal protective equipment (PPE) that typically comprises protective clothing, respiratory protection, a helmet, neck shroud, protective hood, gloves, goggles, and boots (Carballo-Leyenda et al., 2018).

The increasing wildfire activity worldwide requires a higher number of wildland firefighters engaged in fire suppression activities (Koopmans et al., 2022). Anticipating that the number of forest fires is expected to increase in several regions of the globe (Flannigan et al., 2006), it is essential to look for appropriate occupational health and safety measures. Even more, the evidence linking health effects to occupational exposure to wildland fire is still limited and prevention measures are seldom mentioned.

3 But… What Exposures Do Wildland Firefighters Face?

The common hazards that wildland firefighters face on the fire line can include burning over/entrapment, heat-related outcomes, injuries, mental stress, fatigue, dehydration, and smoke inhalation (Britton et al., 2013; Koopmans et al., 2022). Firefighters are highly exposed to harmful pollutants in the form of gases and particles (Smith et al., 2001). Wildfire smoke is a complex mixture containing hundreds of gases and particles such as carbon monoxide, nitrogen dioxide, mono- and polycyclic aromatic hydrocarbons (PAHs), aldehydes, and metals (Naeher et al., 2007). Plus, wildland firefighters are also exposed to other pollutants such as diesel exhaust,

Fig. 1 Firefighters' routes of exposure

since they may be working near vehicles on the fire ground, in another emergency occurrence, or even at the fire station (Horn et al., 2022). Hence, it is very difficult to know all the pollutants or the mixture of pollutants that firefighters are exposed to during their activities and the extent of such exposure.

Wildland firefighters are exposed to fire smoke pollutants through different exposure pathways (Fig. 1), namely inhalation, ingestion, and dermal absorption (Ruby et al., 2002). Inhalation is the main exposure pathway for several harmful compounds that are present in smoke (Heus, 2018). The portion of pollutants inhaled is proportional to the volume of air inspired and expired, increasing with physical efforts (Stec et al., 2020). The typical respiratory protection used by wildland firefighters is a cotton bandana which offers very little protection against particulate matter (PM) due to its poor filtration efficiency, and that does not prevent the inhalation of toxic compounds (Austin, 2008; Heus, 2018; Naeher et al., 2007).

Wildland firefighters may also be exposed to fire smoke pollutants through dermal exposure (e.g., PAHS and volatile organic compounds) (Heus, 2018). Previous research has demonstrated that some pollutants may settle in the exposed skin (Rogula-Kozłowska et al., 2020) or even penetrate the firefighting protective ensemble (Barker, 2005) allowing dermal absorption of those contaminants. These exposures may be enhanced by the inadequate use of PPE or by inefficient decontamination procedures after fire suppression activities (Barker, 2005; Demers et al., 2022). In addition, exposure to high temperatures compromises the skin barrier facilitating the dermal absorption of toxic compounds (Heus, 2018; Wingfors et al., 2018). Absorption increases by 400% for every 5 °C increase in skin temperature (Stec et al., 2020).

In addition, wildland firefighters may be exposed to smoke toxicants via ingestion due to the lack of appropriate PPE (unprotected mouth) or even due to inadequate practices such as eating, drinking, and/or smoking with contaminated hands during or after firefighting activities (Heus, 2018). Moreover, contaminants that enter the upper respiratory tract may be carried via saliva into the digestive system (Stec et al., 2020).

Exposure to pollutants occurs not only during firefighting and other fire operations (e.g., prescribed burning) but also in their return to the fire station via diesel exhaust and contaminated post-fire gear and/or other equipment. The inefficient decontamination procedures of PPE or other equipment used during firefighting also favor cross-contamination in fire stations (e.g., rooms, bedrooms, offices, and garages) compromising the indoor air quality where firefighters spend long periods of their shift (Banks et al., 2021; Oliveira et al., 2017). This may occur due to a lack of knowledge of safety procedures, cultural behaviors, carelessness, or logistical conditions (Magnusson & Hultman, 2015). It should be noted that in some cases, the fire stations are located in old buildings with inefficient ventilation systems that do not prevent or mitigate the spread of pollutants within the indoor spaces (Demers et al., 2022). In this manner, firefighters face a "cocktail" of exposures via multiple routes, leading to potential exposure misclassification that may consequently underestimate firefighters' health risks. Exposure misclassification may explain some of the inconsistencies seen in the epidemiologic literature (Koopmans et al., 2022; Sparer et al., 2017).

4 What Health Outcomes Do Wildland Firefighters Face?

Firefighters face many risks that can cause immediate or long-term consequences on their health and well-being. World Fire Statistics show that, between 2016 and 2020, an annual mean of almost 70.000 firefighters got injured, and 86 firefighters lose their lives during firefighting occurrences (CTIF, 2022). Cardiac events have been considered an important cause of death among firefighters during fire ground operations (Kales et al., 2003; Koopmans et al., 2022). In the USA, for example, sudden cardiac death (usually heart attacks) continues to be the leading cause of death among firefighters on duty (Fig. 2).

These sudden cardiac events have been associated with different factors such as heat stress, exertion, dehydration, shift work, and stress (Guidotti, 2014), as well as with risk factors such as hypertension, diabetes, cholesterol, and lack of physical fitness (Kales et al., 2007). In addition, mortality rates have been largely associated with aviation-related incidents, entrapments, and vehicle collisions (Butler et al., 2017). The last is a common cause of firefighter mortality worldwide and is often related to excessive speed and the misuse of seat belts (International Association of Fire Chiefs, 2008). Besides these immediate negative health outcomes (e.g., life loss, injuries), the real impact on health is much higher, like an iceberg where we only can see the tip and not the whole bulk.

Firefighters are exposed to a wide range of harmful substances, many of them classified by the International Agency for Research on Cancer (IARC) as known (e.g., benzene, benzo[a]pyrene, formaldehyde, and PM2.5) or probable/possible (e.g., acetaldehyde, benzofuran, ethylbenzene, furan, black carbon, and styrene) human carcinogens (IARC, 2010). There are several studies worldwide indicating an increased risk of different cancers among firefighters (Jalilian et al., 2019; LeMasters et al., 2006; Pukkala et al., 2013) such as melanoma, leukemia (Tsai et al., 2015), colon, rectum, testis, thyroid (Jalilian et al., 2019), laryngeal, and hypopharyngeal

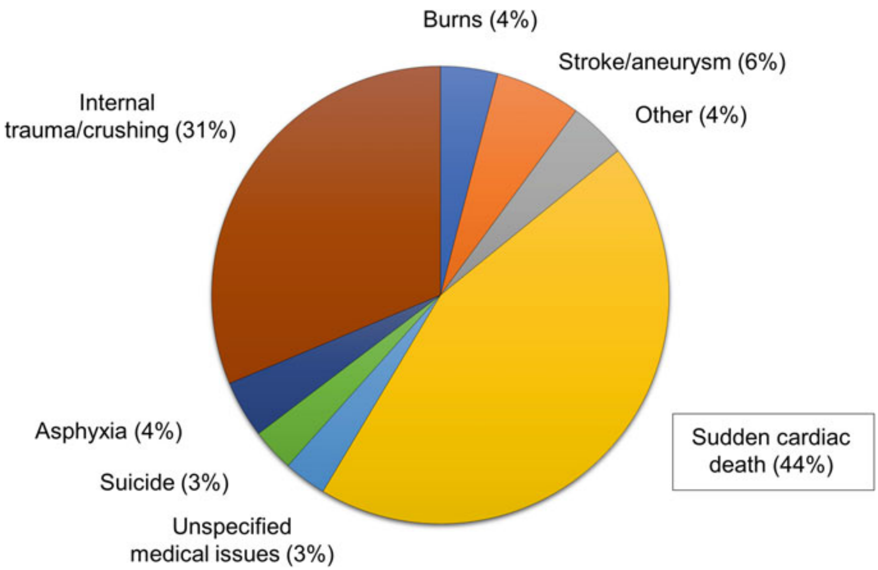

Fig. 2 US firefighters' deaths while on duty: 2021 (Adapted from Fahy et al. [Fahy & Petrillo, 2022])

(Zhao et al., 2020). In this line, in June 2022, occupational exposure as a firefighter was classified by IARC as carcinogenic to humans (Group 1) based on "sufficient" evidence for cancer (bladder and mesothelioma) in humans (Demers et al., 2022).

Not surprisingly wildland firefighting has been associated with other long-term adverse health outcomes such as respiratory (e.g., asthma, chronic obstructive pulmonary disease) (Greven, 2011) and cardiovascular outcomes (e.g., heart attacks, arrhythmias) (Andersen et al., 2017; Fahs et al., 2011; Navarro et al., 2019; Pedersen et al., 2018; Soteriades et al., 2011). The prevalence of self-reported health effects was found to be directly correlated with years of firefighting, and individuals with long careers who have higher chances to develop adverse cardiovascular outcomes (Semmens et al., 2016). According to the National Fire Protection Association, sudden death from a heart event is the most common cause of mortality among firefighters accounting for 40–50% of deaths annually (Fahy, 2005); long-term exposures to cardio-toxic compounds, such as carbon monoxide or PM from fire smoke, have been considered an important factor for vascular diseases (Du et al., 2016).

Other long-term health effects related to occupational firefighting exposure have been described (Jahnke et al., 2018). Previous studies showed that nearly a quarter of US female firefighters' first pregnancy ended in miscarriage (higher than the 10% verified in the general US population) (Jahnke et al., 2018). In addition, the high levels of stress and traumatic situations contribute to firefighters' vulnerability to mental health problems (Walker et al., 2016), leading to substance abuse (Carey et al., 2011), depression (Kimbrel et al., 2011), post-traumatic disorder (Chen et al., 2007), sleep disturbance (Vargas de Barros et al., 2013), and even suicidal behaviors (Boffa et al., 2017).

5 Better Health for Firefighters: Looking at the Preventive Measures

Benjamin Franklin, founder of the first volunteer fire brigade in the USA, once said "An ounce of prevention is worth a pounce of cure" (International Association of Fire Chiefs, 2008). So, the way firefighters can prevent occupational risk in their activity is the responsibility of multiple parts. Compared with some exposures encountered during firefighting, exposures at the fire station may be more easily modified through changes in systems and protocols, representing potential useful intervention targets. Fire stations should have a set of standard guidelines that incorporate safe practices and policies to protect firefighters' safety and health. All staff should be trained in implementing such procedures and, most importantly, guarantee that firefighters are aware of the occupational risks that they face and the importance of adopting preventive measures to reduce or eliminate occupational risks.

Firefighters must know how to correctly use PPE. Equally important is guaranteeing proper maintenance through regular cleaning and inspection of PPE, repairing or replacing it when necessary. During fire suppression activities in the field, firefighters should avoid eating, drinking, or smoking with unwashed hands (Stec et al., 2020). When necessary, they must do so in a suitable environment with washed hands (e.g., water and soap or cleansing wipes) so that contaminants do not enter via ingestion (Magnusson & Hultman, 2015).

Decontamination procedures after exposure to fire pollutants are extremely important (Fig. 3), including decontamination of firefighting personnel as well as of the contaminated PPE/equipment/vehicles (Magnusson & Hultman, 2015). The decontamination procedure is a sequential set of steps that must be followed to ensure a successful decontamination process.

The contaminated PPE and equipment should be cleaned *in loco* wherever possible; if not possible, contaminated PPE should be stored in proper containers/bags and transported separately from firefighters, i.e., outside the vehicle cab (Stec et al., 2020). Firefighters should change to clean and dry clothes before returning to the fire station to reduce skin exposure to contaminants (Stec et al., 2020), or else take off the undergarment as soon as possible on return to the fire station. After fire suppression activities, it is crucial to wash exposed skin areas (e.g., hands, neck, face) with soap and water. When this is not practical, firefighters may use cleansing wipes on exposed skin parts (e.g., neck and hands) to reduce the number of contaminants (e.g., PAHs) (Fent et al., 2017). However, it is important to be aware that some particles and other contaminants might remain on the skin, and as long as contaminant is present on the skin, more time is available to be absorbed (Fent et al., 2014, 2020;

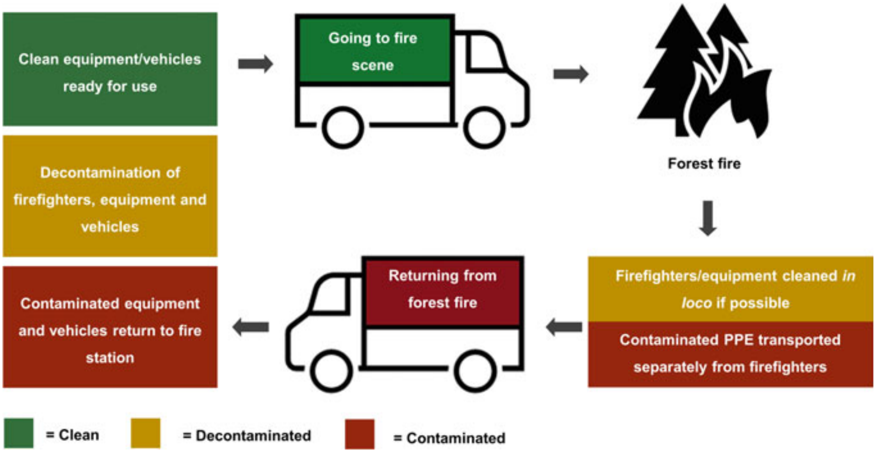

Fig. 3 The (de)contamination cycle (Adapted from Swedish Civil Contingencies Agency [Magnusson & Hultman, 2015])

Keir et al., 2017). As such, showering with soap and shampoo should occur as soon as possible when returning to the fire station.

It is of utmost importance to control the spread of harmful pollutants on return to the fire station through the designation of "contamination zones" and "clean zones." Personal decontamination should be a priority when returning to the fire station from a fire; thus having available showers in the facilities is crucial. Contaminated PPE/clothing must be cleaned/laundered after every fire event, if possible, in a special designated area "contaminated zone" of the fire station to prevent cross-contamination. During these procedures, it is important to protect areas of exposed skin (e.g., gloves) and airways (e.g., face mask) (Stec et al., 2020). Besides PPE, work tools and vehicles should also be cleaned and decontaminated regularly (Stec et al., 2020).

Construction of fire stations must be designed considering a specific layout (based on the circuit of "contaminated" and "clean" areas) and proper engineering measures to guarantee a clean airflow within spaces. The implementation of efficient ventilation systems must be a concern, particularly in the areas of the fire station where contaminated material is handled. The air quality of fire stations should be regularly monitored to guarantee safe exposure levels to air pollutants (Slezakova et al., 2022). Preventing contamination will keep firefighters and other fire station personnel protected from smoke-related contaminants.

Firefighting is a highly physically demanding activity that requires a good fitness level including aerobic fitness, anaerobic capacity, muscular strength, and endurance. The development and implementation of well-designed fitness programs that encourage physical activity and a balanced diet (e.g., water, fruits, vegetables, whole grains, and low-fat foods) are critical for the promotion of health and well-being among these individuals. In addition, regular health screening should be provided to firefighters to early detect any adverse health events. Understanding the impacts of wildland fires on firefighters' health can help to design mitigation strategies and efficient policies to protect their health.

6 Taking Care of Firefighters' Health in a New Era of Forest Fires—The Portuguese Reality

There are around 27.000 firefighters in Portugal (81% males and 19% females), distributed by 465 fire stations, of which 63% are volunteers and 37% are professional, with ages comprised mostly between 26 and 50 years and the majority with 12th grade of scholarly (INE 2020). A recent study found that 80% of a group of Portuguese wildland firefighters reported being exposed to smoke, gases, and particles during their activities (Esteves et al., 2022b); this finding is particularly concerning due to the long careers (average of 16 years) and the long periods of work that were described (i.e., the majority claimed to work in firefighter activities more than 10 h/day) (Esteves et al., 2022b).

Portugal is one of the European countries most prone to wildfires (Beighley & Hyde, 2018). On average 3% of Portuguese forests burn annually (Schleussner et al., 2019), corresponding to around 100.000 hectares. However, this trend has been increasing through the years (Schleussner et al., 2019); from 2008 to 2017, for example, the annual burned area varied from 18.000 hectares to 500.000 hectares (Schleussner et al., 2019).

The evident demographic shifting of the population moving from rural to urban areas, the highly fragmented and unmanaged private forested lands, the typically evergreen and drought-resistant vegetation, the high number of human-cause ignitions (negligence or intentional), and climate changes (high temperatures and decreasing precipitation levels) all contribute for the increased risk of forest fires (Beighley & Hyde, 2018; Carmo et al., 2011; Nunes et al., 2005). In December 2019, the European Council recognized that Portugal is one of the European countries most affected by climate change (European Commission, 2019). Portugal has already experienced severe heat waves, storms, and droughts (Schleussner et al., 2019). During the extreme wildfires of 2017, a record of burnt areas was registered in Portugal (500.000 hectares) and 120 human lives were taken (Turco et al., 2019), including firefighters' lives. European Union Joint Research Center (EU-IJR) forecasts an increase in forest fire danger, particularly noticeable in the Southern countries including Portugal (Fig. 4).

On the contrary, the number of Portuguese firefighters (professional and volunteer) has been decreasing through the years registering a drop of 33% in just a decade (Fig. 5) (Beighley & Hyde, 2018; PORDATA, 2020).

Firefighters are crucial human tools in forest fire defense. Thus, efforts should be done to retain experienced firefighters and to attract younger people to this workforce creating attractive remuneration conditions (e.g., higher wages) and improving

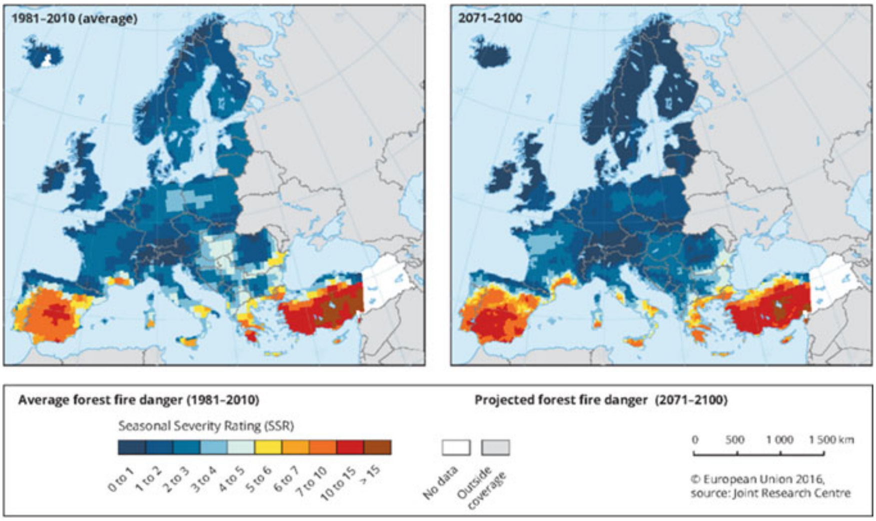

Fig. 4 Historical and future trends of forest fire danger in Europe (Retrieved from EU-IJR [European Commission, 2019])

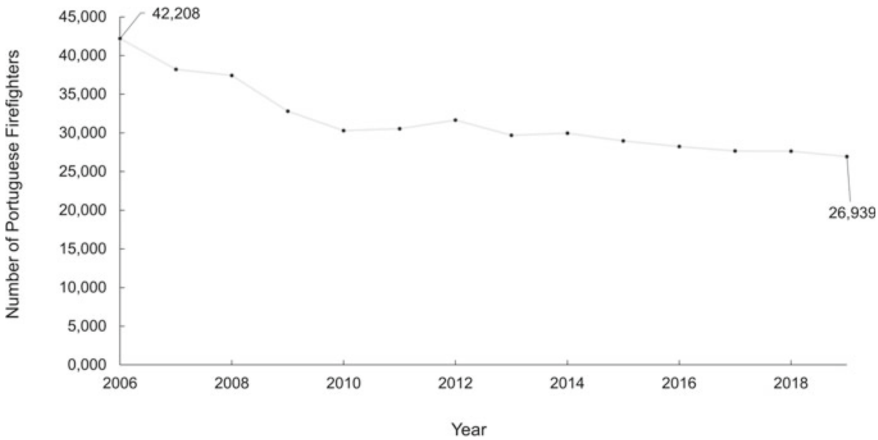

Fig. 5 Number of Portuguese firefighters over the years (Adapted from PORDATA [PORDATA, 2020])

health and safety conditions (Beighley & Hyde, 2018). Surveillance based on monitoring programs (biological and environmental) may be a possible solution to identify potential occupational risks and their impact on firefighters' health.

7 Conclusions and Recommendations

The implementation of a comprehensive set of preventive measures must be a priority to reduce fire occurrences and resulting damages. This is particularly relevant because, during the past decades, we have witnessed a rise in forest fires (i.e., number and severity) driven by unusually high temperatures. Government is a vital stakeholder in better structuring forest policies and providing the resources needed to prevent and deal with forest fires. Prevention efforts across different scales are essential for the success of a forest fire prevention system. Prescribed burning, fuel breaks, water reservoirs, forest access roads, meteorological warnings, and information campaigns to promote the individual responsibility of citizens are examples of some important and effective preventive measures. In parallel, it is crucial to strengthen the fire response structure so that forest fires can be rapidly detected and suppressed at early stages, preventing human and ecological loss/threats. Having healthy and well-prepared firefighters is essential to save human lives and preventing forest fires from escalating. Thus, efforts must be done to implement appropriate practices and policies to promote health and safety in this workforce.

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The Cost of Forest Fires: A Socioeconomic Analysis

Zoran Poduška and Snežana Stajić

Abstract This chapter aims to show the phenomenon of forest fires from socioeconomic aspects to present the readers with a new perspective. We start from the assumption that fire in forest ecosystems has a positive and negative impact, which can be represented by an appropriate valuation system. The basis for such an assumption was found in the paradox of fire (in natural ecosystems), which has had human attention from the very beginning of the human population. From early views on social dependence on fire to a modern perspective, that fire is a catastrophic phenomenon in nature. Today, it can be assumed that our valuation system is set at a point where fire harms nature. This tacit acceptance has become commonplace in fire reporting where the importance of fire in removing biomass especially coniferous stands, maintaining open spaces for grazing and hunting, reducing catastrophic wildfires, in carbon balance and water regulation or scientific knowledge is almost completely omitted. Contemporary streams in nature and forest science and practice point out that fire is an ecosystem service providing many services with trade-offs between fire prevention and the provision of ecosystem services. Here, we explain why fire in natural ecosystems become relevant for science after the eighties. We present that the extent of fire damage is more than 0.012% of Worlds GDP in this decade. Major socioeconomic driving factors of forest fires are presented too. The chapter presents examples of ecosystem services and economic impacts provided by wildfires.

Keywords Wildfire · Natural disturbance · Ecosystem services · Valuation · Human well-being

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1 Introduction

Socioeconomic analysis of forest fires is a two-way process. It could be analyzed by the role of socioeconomic factors in driving forest fire activities and analyzed as well in the allegedly opposite direction as the role of forest fire on society, economy and environment. But this is not the final division of forest fires from a socioeconomic aspect. Forest fires at the same time are considered occurrences with damages (Sil et al., 2019) and occurrences with benefits (Pausas & Keeley, 2019). Analyzing these opposite views, here, we primarily accepted the use of the term fire instead of wildfire. Term fire in socioeconomic and valuation studies enables a more balanced perspective of positive and negative contributions to human well-being (Shackleton et al., 2016; Pausas & Keeley, 2019).

Following such opposed attitudes regarding fire but with the orientation toward neutral analysis, it is justified to use the perspective that fire in natural ecosystems has dual effects on human well-being. In literature, this perspective is embedded in an ecosystem services–disservices perspective (de Groot et al., 2002; Shackleton et al., 2016; Depietri & Orenstein, 2019). This perspective indicates that fire can in some cases decrease human well-being and then we call it disservices (Shackleton et al., 2016) on opposite fire in some cases can increase human well-being and then we call it services (Pausas & Keeley, 2019). Following that perspective, our analysis is based on the assumptions that fire in forest ecosystems has a positive and negative impact, which can be represented by an appropriate valuation system.

The basis for such an assumption was found in the fire paradox (in natural ecosystems), which has had human attention from the very beginning of the human population. In the scientific community by fire paradox sometimes is understood as a situation when the results of research about fire are opposite of what scientists were going to find (Georgiou, 2022). Fire as a global and regular component of forest ecosystems consist of several paradox, too. The first and most recognizable paradox is placed in the traditional phrase[1] about fire as a master and a servant. This phrase carries a strong message that fire is useful when monitored and controlled however, left unattended, it is quite dangerous and destructive (Hills & MacGibeny, 2015). The next paradoxes are derived from the tacit acceptance that forest fires are destructive disturbances leading to very costly, extremely damaging effects on nature (Lynch, 2004). For example, newspapers and magazines report a catastrophic forest fire, but only 1% of all forest fires become catastrophic. It is completely justified to ask what the character of other forest fires is that gives us the epithet of catastrophic. The answer is not simple or is already contained in the view that the emergence of forest fires as a global and regular component of the forest ecosystem consists of paradoxes connected with the value of ecosystem products and services from a socioeconomic perspective.

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[1] "*Fire is a good servant but a bad master*".

2 Valuation Studies Related to Forest Fire and Socioeconomy

Here, we analyze the phenomena of a forest fire from a socioeconomic perspective based mainly on valuation studies. The analysis starts with the search for appropriate documents in scientific databases. Scientific interest in fire in natural ecosystems is relatively new, which is presented in Fig. 1.

We used the Scopus (2020) scientific journal database that served us for the socioeconomic analysis of forest fires. We analyze scientific articles containing the terms fire/wildfire/cost in titles, abstracts and keywords. Most of the articles were published in the USA, Canada and Australia. In Asia, most of the papers were published in China and India and Europe in Spain, the UK, Italy and Portugal. Figure 10.1 presents the number of documents, mainly research papers in scientific journals with thematic of the valuation of the forest fires. The number of documents is presented per country, funding sponsor, subject area and year.

Increasing interest in fire is especially noticeable at the end of the ’80s. This interest is explained by the occurrence of large fires that are broadcasted by media on a global scale. It is directly related to Ash Wednesday bushfire in Australia at the year 1983 and the forest fire in Yellowstone National Park (NP) at the year 1988. Forest fire in NP Yellowstone lasted longer than three months over an area of more than 1.400.000 ha with suppression cost of $120 million and 25.000 firefighters, until the evening of September 14, when approximately 1 cm of snow fell, extinguishing

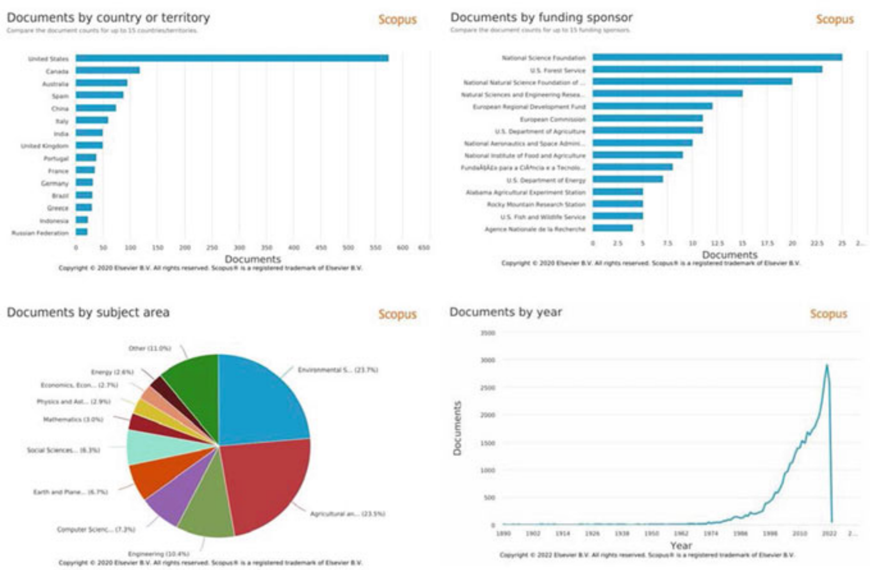

Fig. 1 Documents with thematic forest fire/wildfire and cost in Scopus

the fire (Keeley, 2009; Wallace, 2004). This sequence of events indicates that (this) fire in NP Yellowstone is a natural phenomenon that occurs every 300–400 years due to a specific meteorological phenomenon as a result of a combination of drought, temperatures and dry thunderstorms with lightning strikes and high winds (Wallace, 2004). After that, there was an almost exponential growth of published papers in scientific journals related to fires in the period 1985–1995 (Keeley, 2009).

2.1 Role of Forest Fire on Society, Economy and Environment

The growing interest of the scientific community in fires in natural ecosystems was followed by the formulation of several hypotheses and theories from a socioeconomic aspect. Such theories and hypotheses are (i) the grandmother hypothesis; (ii) the bipedalism hypothesis; (iii) the fire in nature as extraterrestrial origin hypothesis; (iv) the pyrodiversity–biodiversity hypothesis and (v) the Pyrocene theory.

One of the oldest social impacts of fire on humans is illustrated through the interpretation of the "grandmother hypothesis." It implicated that by softening food, the fire could have had a large effect on extending the human life span beyond the age of good-quality teeth which is related to child care by grandmothers and with social development and human evolution (Hawkes, 2004).

Bipedalism as a significant part of hominization is hypothesized to have some connections with fire-prone regions. The origin of human endurance bipedal could be connected with collecting underground plant structures widely spaced in fire-prone ecosystems (Lieberman, 2013). Such plants protect themselves from fire by growing belowground storing carbohydrates as a significant part of human dietary differences.

Among all other natural disturbing processes on Earth, fire has been hypothesized to have in some occurrences extraterrestrial origin, especially in Pleistocene megafauna demise (Firestone et al., 2007). Contrary to other natural hazards such as earthquakes or windstorms, wildfires are certainly among the most predictable ones (Birot, 2009). Multiple ecological hypotheses suggest that high pyrodiversity will lead to high biodiversity (Jones & Tingley, 2022). The hypothesis that "pyrodiversity begets biodiversity" still lacks in the synthesis of findings (Bowman et al., 2016) but there is an initial and contemporary theory. Fires as agents of biodiversity hypothesized that prehistoric fire regime promotes diverse biota but contemporary theory suggests that after many decades of fire suppression, we have reduced pyrodiversity which can lead to reduced biodiversity (Martin & Sapsis, 1992).

The Pyrocene theory reveals that Planet Earth is entering the age of mega-fire where there is no place for fire naivety (Nimmo et al., 2021). In today's fire-centric perspective, humans continue to shape the Earth in a specific pact with fire. Both fire and people exist in a mutual-assistance pact, but where humans could not

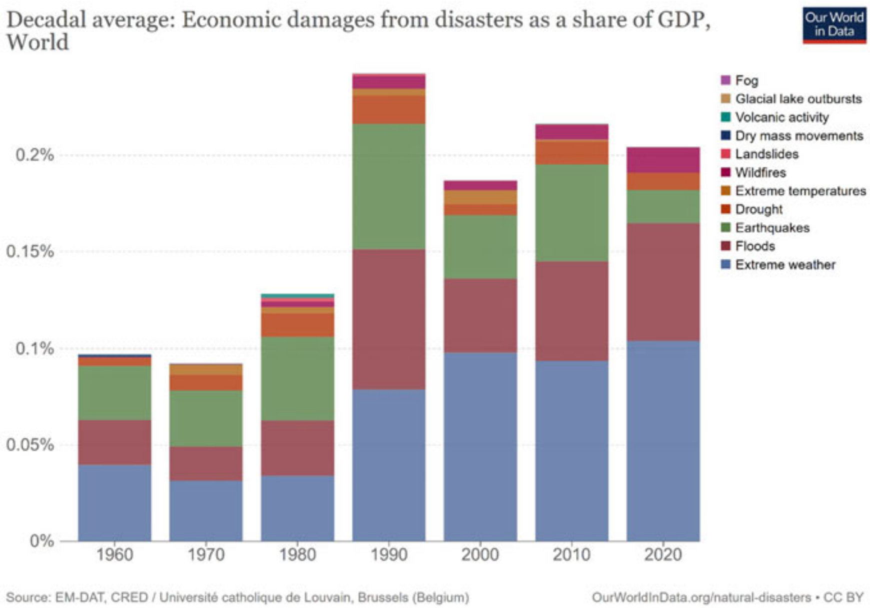

Fig. 2 Damages from fires among natural disasters as a share of GDP—world scale. *Source* (Ritchie et al., 2022)

exist without fire. Especially without the so-called "third fire" which is industrial combustion (Pyne, 2022).

2.2 The Cost of Damages from Fires as Natural Disaster

Today, it can be assumed that our valuation system is set at a point where fire harms nature. In that sense, reports about natural disaster damages from fires are presented too. The first global assessment of damages from fires counted from the decade 1960 and it is presented in Fig. 2.

The assessment indicates that the damage from the fire is $7.06B (Ritchie et al., 2022). According to the same source, the extent of fire damage varies across continents. In America (North and South), economic damages from wildfires are assessed at $6.65B, in Europe $282.67 M, in Asia $77.33 M, in Australia and Oceania $43.3 M, and without estimation for Africa. The damages from the fire are also assessed as a share of GDP.[2] The total share of damage from a fire disaster in GDP is highest in the ongoing decade 2020 and it is more than 0.012% of GDP, for the decade 2010 (> 0.007%). From 2000 to 2010, it reached > 0.005%, in the decade 1990 > 0.006%, and from 1980 to 1990 > 0.003. Finally, from 1960 to1970, the numbers reached <

[2] Gross domestic product.

0.001%. In more than 60 years, damages from fire as natural disasters increased by almost 12 times according to the share in GDP.

2.3 Socioeconomic Factors in Driving Forest Fire Activities

More than 90% of the forest fires in Europe are caused by human activities, behaviors and attitudes (Barbero et al., 1990; Martinez et al., 2009). In an econometric analysis, Michetti and Pinar (2013) revealed some major driving factors of forest fires (Table 1).

Specific patterns, frequency and affected area reveal that forest fires are not only related to meteorological and climate conditions (Ratknić, 2019) but also to socioeconomic causes (Birot, 2009). The ignition, in most cases, is related to human activities (agriculture, forestry, garbage removals or power lines) and behavior (recreation, delinquency or smoking) (Barbero et al., 1990; Catry et al., 2010; Martinez et al., 2009). Fire occurrence could be accidental too, although fires are considered catastrophic natural disturbances. However, human influence on fire is the greatest compared to all other natural disturbances. Regardless of economic and technological development, humans still have management authority over the fire, while storms, hurricanes, earthquakes and volcanic eruptions have no influence.

2.4 How (Fire in) Nature Always Works for the Benefit of Humans

The attitude toward fire in the sense that it is a benefit has its origins in the Utilitarian theory which addresses that nature always works for the benefit of humans. Based on similar premises, Pausas and Keely (2019) summarized the benefits to humans of living in a flammable world, even if it is well-known that forest fires are far from natural origins. These premises are criticized to be conceptually incorrect and misleading to policymakers and resource managers (Sil et al., 2019). Table 2 presents examples of ecosystem services provided by recurrent wildfires.

Fire as a tool for nature management is mainly related to primitive man who, when he "learned" to use it, provided himself with heat-treated food, increased soil fertility, regenerated natural vegetation for grazing and controlled competing vegetation (Damianidis et al., 2021). Contemporary streams in natural and forest science and practice point out that fire is an ecosystem service (Pausas & Keeley, 2019) providing many services with trade-offs between fire prevention and the provision of ecosystem services (Mavsar et al., 2013). Forest ecosystems fulfil a multitude of functions and services simultaneously including, producing timber and biomass, protecting the soil from erosion, and recreational tourist, spiritual and cultural experiences. In such an environment, the occurrence of various disturbances is expected. Fire is one of the most predictable disturbances that can be expected to have both

Table 1 Major driving factors of forest fires (Michetti & Pinar, 2013)

Cause	Impact on fire	Description of impact
Population density	Mixed	More urbanization reduces impact due to proper land management close to fully biomass removal as potential source of fire More human nature interaction increases possible accidental fire ignition
Infrastructures	Mixed	A greater number of roads and railways may put more pressure on wild lands raising possible ignition causes. Nevertheless, good communication routes may help fire prevention and suppression
Agriculture and pasture intensification	Mixed	Fire is often used by shepherds and farmers to (i) maintain herbaceous vegetation only; or (ii) eliminate wasting harvest in borders of croplands, (iii) remove pests
Education	Negative	More educated people may have a higher civic sense which helps containing the number of fires due to human perverse behavior or accidents
Unemployment total/ male/female; poverty level	Positive	Higher unemployment levels may provoke people from setting forests on fire for profit reasons
Depopulation of rural areas	Positive	It contributes to land abandonment and spontaneous colonization of natural vegetation with leading to increment in forest biomass, and consequently in greater forestland flammability
Tourism	Mixed	Tourism in forests areas could raise the probability of ignition by accident or negligence (campfires, smokers) From the other side management of forest recreation areas could decrease probability of forest fires
Presence of illegal activities	Positive	Initiation of forests fires to gain land for agriculture or pasture, tourism and recreation
Railway density	Positive	Improving safety in the railway network is expected to have a supportive impact in reducing fire events
Grazing activity by domestic animals (cattle, goats, sheep, horses, donkeys, pigs)	Mixed	Bovine grazing, which has almost no impact on reducing fire frequency, seems to help in containing the spread of fire The presence of caprine animals affecting positively both fire frequency and extension
Educational level in population	Negative	Increasing education levels decreases frequency and intensity of fires
Employment in the: agricultural/industry sector	Mixed	Agriculture activity puts pressure as well as generates protection against, forest fires Mixed effects but confirming a link between profit motives and forest fires

(continued)

Table 1 (continued)

Cause	Impact on fire	Description of impact
Criminal activities	Positive	Illegal activities have impact on fire frequency, but no impact on the total area burnt
Policy aspects/forest management plans	Positive	Coniferization increase possibility of fire occurrence and spreading

Source (Michetti & Pinar, 2013)

positive and negative impacts on possible objectives of ecosystem management (Silva et al., 2010; Keely & Pausas, 2022).

Supporting services are necessary for the production of all other ecosystem services (MA, 2005) where forest fires contribute to a range of ecosystem services. Some of these services are pollination, the evolution of a diversity of shade-intolerant plants, habitat heterogeneity, and breaking physical dormancy in forest tree seeds.

One of the oldest provisioning services lasting today, and as we mentioned above, it has been hypothesized that fires are agents of biodiversity (Martin & Sapsis, 1992). Humans can modify the landscapes through fires as a powerful ecological force that can positively or negatively affect the risk of economically disruptive fires by reducing catastrophic fires (Bowman et al., 2016). But reductions in burn probability are not always beneficiary. It depends on the site-specific consequences of fire (Thompson et al., 2017) and it might be desirable to increase the conditional probability of low-intensity fire for restoration objectives (Ager et al., 2013).

3 Economic Impact of Forest Fires

To better understand the economic impact of forest fires, Table 3 presents the costs derived from large fire occurrences based on Diaz's (2012) analysis.

The impact of large forest fires is presented in several cost types: natural areas, local community, business, suppression costs and post-fire rebuilding. Fire affects products and services in natural areas. The cost of timber affected by the fire is assessed at $2.995/ha. The cost of watershed protection as a regulatory ecosystem service is assessed at $311/ha.

Local communities as well lose significantly from forest fires through lack of tourist visits, infrastructure and property damages, and harm to residents and fire-fighters. Tourism losses are $682/ha when closing natural areas during and after the forest fires. Property losses calculated by damaged or lost homes are assessed at $59/ha. Effects of smoke on health are assessed through medical costs of $72/ha and suppression cost reaches $494/ha.

In an economic analysis of the impacts of wildfire, it is concluded that positive effects come from the economic activity generated in the community during fire suppression and post-fire rebuilding (Diaz, 2012). Besides suppression costs, local

Table 2 Examples of ecosystem services provided by recurrent (wild)fires

Type of ecosystem services	Examples of ecosystem services provided by (wild)fires	Used by human societies
Supporting	Formation of open habitats that enable the evolution of a diversity of shade-intolerant plants	Early
	Enables evolutionary processes (via natural selection and evolution) and ecological processes (via habitat heterogeneity) or breaking physical dormancy in forest tree seeds	Early; contemporary
	Species conservation, including the conservation of some ecological processes (e.g., pollination)	Early; contemporary
Provisioning	Provide open spaces for pastures, agriculture and hunting	Early; contemporary
	Stimulate germination of desirable annual "crops" post-fire	Early
	Provide carbohydrates from underground plant organs	Early
	Provide craft and basketry material (resprouts)	Early
	Maintain open spaces for grazing and hunting	Early; contemporary
	Provide essences, medicines, and flowers (ornamental)	Contemporary
Cultural	Spiritual	Early
	Ecotourism in open ecosystems	Contemporary
	Recreational hunting	Contemporary
	Scientific knowledge about the origin of biodiversity	Contemporary
	Information about ancestral fire management techniques	Contemporary
Regulating	Pest control for humans and livestock	Early, contemporary
	Reduce catastrophic wildfires	Early, contemporary
	Accelerate species replacement under changing conditions	Early, contemporary
	Enhance flowering and pollinator activity	Contemporary
	Water regulation	Early, contemporary
	Carbon balance	Early, contemporary

Source (Keeley, 2012; Pausas & Keeley, 2019)

Table 3 Economic impacts of (wild)fire (Díaz, 2012)

Type	Cost per ha in $
Timber	2.995
Fire suppression	494
Disaster relief	124
Property losses	59
Tourism	682
Watershed protection	311
Estimate of lost business economic activity	2.402
Home, business and property loss	7.658
Medical costs	72

economies affected by the fire can have future benefits fire has a positive influence on economic activities. These economic activities are building and maintaining fire lines in forests, which can be supported by Government funds, investments in wildfire education from the elementary school level (Đorđević et al., 2022), restitution of forests affected by fires (Ratknić et al., 2017, 2021) or by investments in agroforestry (Damianidis et al., 2021).

4 Conclusions and Final Remarks

In this socioeconomic analysis of forest fires, we first challenge the tacit acceptance of the catastrophic character of forest fires where the importance of fire as an ecosystem service is almost completely omitted. Official statistics include only the value of lost market goods and services, according to market prices (Mavsar, 2009) and this is not enough for a neutral assessment of the socioeconomic impact of forest fires. National perspectives of wildland fire patterns and challenges in Europe indicate that detailed studies on socioeconomic impacts are currently scarce (Fernandez-Anez et al., 2021). However, here presented analysis reveals that forest fires cause significant damage to natural products and services, but they can generate income for local communities. In a contemporary approach, the socioeconomic aspect of forest fires should answer the values we are protecting, rather than only the values lost (Mavsar, 2009). Only comprehensive information about the negative but also the positive impact of forest fires especially large ones can help public officials, community leaders and citizens understand the impacts on economies and society.

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The Mediatization of the Resilience Frame: A New Understanding of Wildfires in the Spanish Mainstream Media (2017–2021)

Enric Castelló

Abstract This book chapter offers a media frame analysis on forest fires in the Spanish mainstream media. Three of the most important newspapers are studied in relation to the presence of two media frames: the suppression frame and the resilience frame. After inspecting news and opinion pieces about wildfires during the last five years (2017–2021), the author identifies that the resilience frame is gaining prominence in the media. This interpretative frame emphasizes a discourse of climate change and management transition in which the need of new policies and measures are at the centre of the story, as opposed to the suppression frame treatment of fire as a "fight" or even a "war". The chapter ends by pointing out some challenges that this resilience frame confronts in the face of a mediatization of wildfires and an increasing presence of specialized sources pointing out the complexities of fires in a more reflective manner.

Keywords Media coverage · Wildfire mediatization · Framing wildfires · Resilience narratives · Risk communication · Rural agency

1 Introduction

The media coverage of wildfires has increased during the last five years. During this time, spectacular and uncontrollable wildfires have hit places such as California (2018, 2020, 2021), Australia (2019), Brazil (2019) and Chile (2017), affecting wild–urban interfaces. Fires have also become a major media issue in the Mediterranean countries, especially after severe episodes in Portugal (2017), Greece (2017, 2021) and Turkey (2021). Some of these were labelled "superfires", or 6th generation fires, a technical reference to several elements (including vegetation continuum or global warming) that provoke fire storms and special conditions making them impossible to extinguish with human resources.

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Spain is on the list of countries that have faced this new reality. Spain's firefighting division is regarded by policymakers as one of the best-equipped and most experienced in Europe (EFEVerde, 2019). But the new context requires the fire strategy to be rethought worldwide so that the focus on extinction and suppression shifts to a focus on resilience. This involves the ability to prepare for fire, to adapt landscapes and to sensitize societies to understand that suppression is not enough to respond to the new sort of superfires. The paradigm requires a new public explanation of fire. However, society's understanding of complex issues does not change overnight. This is particularly true when the general public is not prepared for a narrative to be suddenly disrupted, which is the case of Spain, where the paradigm of "fighting the fire" has been hegemonic since the middle of the last century (Seijo, 2009b, Gonzalez-Hidalgo et al., 2014).

However, in recent years, and for various reasons, a new resilience frame has permeated the Spanish public sphere. In this book chapter, we explore how this has happened and we will discuss how these renewed understandings of wildfires must rise to the challenges in the media. The starting hypothesis of the research was that in the last five years, a new discourse of resilience has been occupying mainstream media in parallel to an intense process of the mediatization of wildfires. To check this hypothesis, we tracked three mainstream newspapers for five years, exploring the contest between the two frames (extinction and resilience). We will present how the process evolved, how resilience threatens the hegemonic position of extinction and the challenges that resilience communication faces within this process.

2 Theoretical Backgrounds

Our research relies on media frame theory. The meaning of "resilience" for scientists and social agents has changed during the last decade, due to social understandings of "failed attempts of control" (McGreavy, 2016, 117). In the Spanish case, the suppression frame became hegemonic when, as Francisco Seijo holds (2009a, 2009b), it was sponsored by the government during the dictatorship (1939–1975), policies of reforestation (with single species) and afforestation were implemented, and country folk were encouraged to migrate to cities. This was at the origin of the state-sponsored discourse of fire as "the enemy". Seijo (2009a, 116) claimed that in the 1980s and 1990s, the suppression frame was revamped to digest environmentalism and address the new eco-regionalist and urban public. The epitome of this strategy was the well-remembered campaign entitled "Todos contra el fuego" (All of us against fire), which added an activist aesthetic to the state's objectives so that they became a sort of demonstration involving urban people, farmers, and celebrities.[1] The suppression frame was also popular in the press, which propagated its main features.

[1] This institutional campaign is available at https://youtu.be/RqWwHEEdc4o.

According to González-Hidalgo et al. (2014), the resilience discourse about wildfires started to circulate in Catalonia at the end of the 1990s, after two summers of destruction and the tragic fire of Horta de Sant Joan, led by the Grup de Recolzament d'Actuacions Forestals (Forest Action Support Group) (GRAF),[2] and particularly by the figure of Marc Castellou. They differentiated the resilience discourse from the capitalist, the green and the rural idyll discourses. The resilience frame has a greater technical and scientific component, due to the considerable advances in forest science in recent decades. To understand the rise of resilience as a discourse, we need to consider the advanced levels of the mediatization of wildfires it is being fuelled by. This mediatization involves not only the proliferation of media discourse about wildfires but also the transformation of the institutions that adapt and adopt media logic. Social and cultural mediatization is mostly related to this notion of transformation of institutions, organizations, and structures (Fredriksson et al., 2015; Hjarvard, 2008; Krotz, 2009). It is also a process that has an impact on the constitution of media frames (Castelló, 2012; de Vreese, 2014). It is a two-way relation: mediatization requires organizations and institutions to go beyond adopting media logic (Altheide & Snow, 1979) so that they can respond to these logics by injecting media content and formats with their conceptions of the world. The process works, for example, by putting firefighter commanders in front of the cameras to explain a situation, or digesting scientific output in graphs and pictures to be aired or published in the media. On the other hand, media treatment itself causes changes in the frames, whether they are sponsored by political, scientific or non-expert sources. For example, complexities that are difficult to explain in the media can be discarded because of technical limitations, aspects closer to the editorial line can be focused on, etc.

Although there are a wide variety of discourses and we are aware of the danger of dichotomizing the richness of the narratives available to us, we have decided to track the confrontation of a still hegemonic suppression frame, which still has a lot of life left in it as we shall see, and the emergence of a resilience frame in the media. We use Robert Entman's scheme (1993) to identify its framing elements. The *suppression frame* conceives fire as a disruptive catastrophe, a disaster. In particular, the frame explains fire in terms of individual causation (Castelló & Montagut, 2019). The media will likely report on criminal prosecution, imprudence and fatalities. As part of the construction of the frame, the story of suppression also uses metaphors and other rhetorical figures. This discourse also includes metaphors articulating FIRE AS A MONSTER (Matlock et al., 2017) or as an evil living creature to be defeated. It also focuses on the suppression and extinction themselves, with particular emphasis on the methods used, the number of firefighters, trucks, helicopters, etc., and details about the institutions taking part (regional, national, etc.). Therefore, the issue is also politicized, as it was in Greece (Hovardas, 2014; Karyotakis, 2021). The suppression frame incorporates political responsibility, although it focuses not on policies of prevention on aid for the area and affected farmers. Local people are seen as passive evacuees or as victims in dramatized stories.

[2] Special section of Cos the Bombers de Catalunya (Corps of Firefighters of Catalonia).

In contrast, the resilience frame considers fires as natural phenomena we have to live with and claims that the strategy of "fighting" is limited and can be counterproductive. According to this frame, forests are habitats that need to be managed with innovative techniques such as prescriptive burns and traditional methods such as fuel thinning and sustainable and planned grazing mostly by extensive farming and shepherds' activities. This discourse is masterfully expressed in documents by institutions such as the Forest Sciences Centre of Catalonia and the Pau Costa Foundation, which point out the importance of prescribed burnings or so-called "good fires" (controlled, small) to prevent "bad fires" (out of control, huge). Though the resilience frame is grounded in technical understandings of fire behaviour, it also relativizes a single technological response for suppression and activates pedagogical and sociocultural tools for prevention (Ballart et al., 2016a, 2016b; Plana et al., 2016). This frame also uses a set of lexical markers, including technical and prescriptive burnings, burnt patches, agroforest mosaics, or forestry works and management. The personification or use of metaphors on fire articulates a discourse that WILDFIRES ARE (SOMEONE/SOMETHING) TO BE UNDERSTOOD. In this discourse, local people are part of the solution because they actively help to prevent and avoid exposure to megafires.

Having described both discourses, to conclude this theoretical approach, we remark on the links between discourse and action, and therefore transformation. In this respect, we find particularly appropriate to consider framing as a process that projects vectors for social transformation (Castelló, 2019). Under this rationale, the role of the media (including social networks, campaigning, grassroots media production, etc.) is at the core of resilience production processes and organizational change. In that sense, we agree with those authors that consider that the media are crucial if social and political responses to wildfires are to be enhanced, so that "pathways to resilience in socioecological systems" can be found (Moritz et al., 2014).

3 Methodological Note

In this book chapter, a textual analysis was used to assess the presence and importance of the resilience frame in the media. The corpus consisted of the materials published in the *El País, El Mundo* and *La Vanguardia* between 1 January 2017 and 31 December 2021 containing the expressions *incendio(s) forestal(es)* (forest fire(s)).[3] After duplicates and non-relevant materials were discarded, the search produced a corpus of 656 pieces. We analysed the corpus using the qualitative data analysis tool Atlas.ti (22.2.0, Berlin, Germany) and applied a codification to test the presence of the resilience frame.

[3] The search engine database used was Factiva. According to the data available from Asociación para la Investigación de Medios de Comunicación, and after discarding the two leading Sports dailies (Marca and AS), these are the most read newspapers in Spain in 2020. Source: https://www.statista.com/statistics/436643/most-read-newspapers-in-spain/.

Table 1 Summary of subcodes

Suppression	Resilient
Fight: the story remarks on the fighting towards wildfires	*Resistance:* the story focuses on the resilience of nature and species
Politization: political dispute and political reactions during the crisis. short-term aids	*Policing*: policies proposed, organized actions. Long-term investment
Individual causation: focus on single causes (e.g. arsonist)	*Structural causation*: focus on structural issues (e.g. global warming)
Low agency of locals: neighbours as victims	*High agency of locals*: neighbours as agents
Neutral/Transversal elements: elements focusing on risk (e.g. during heat waves) or the damages caused by the fire (human, material, natural)	

Source author

We used four categories: resilience, suppression, both-relevant and no-framed. The frames were identified with the subcodes expressed in Table 1. The category of both-relevant contained pieces with a mixed, complex story using both frames, whilst no-framed covered an issue beyond our scope. After testing the codes, we read all the pieces and evaluated each of them. The length of the pieces was not considered. To be assigned to a frame, the pieces should contain at least one feature considered to be a subcode and display the frame, albeit partially, throughout the textual device. We examined up to 2662 quotations within the pieces, and we took notes and worked on memos until each piece was balanced and allocated to one of the previous categories.

When the piece mixed both frames, with textual devices in quantity and quality, it was labelled as both-relevant. This label was restricted to relatively long items containing elements from both frames, with arguments and devices that activated both understandings of the discourse. Not all the pieces were assigned to a frame. Topics and ideas related to risk, warnings or precautionary measures at critical moments or fire damage were considered to be neutral because they can be articulated equally in both understandings and rationales. Although the big picture was portrayed by quantitative data, it was the qualitative analysis that more clearly reflects how the discourse of suppression stands in the media.

4 Results

The coverage of wildfires (Fig. 1) shows that there were more news items in the years with more incidents (2017, 2019 and 2021). However, other issues also deserve to be mentioned. For example, the years 2020 and 2021 were quite similar in terms of the number of fires (2671 and 2914, respectively), and even though there were more big fires in 2020 than in 2021 (19 and 18, respectively) (Centro de Coordination de la Información Nacional sobre Incendios Forestales, 2021), the data reveal a greater focus in the last year. *El País* was the newspaper that paid the most attention

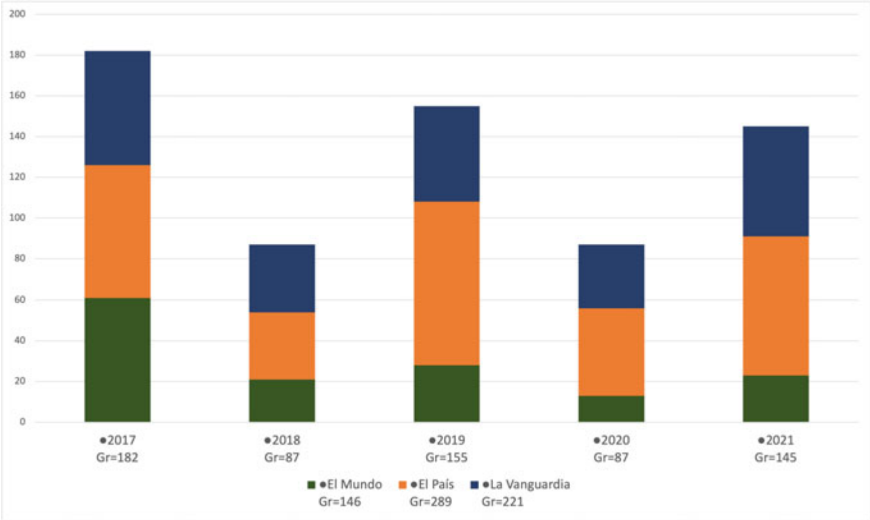

Fig. 1 Coverage of wildfires in the newspapers, 2017–2021 ($n = 656$)

to the topic, followed by *La Vanguardia* and *El Mundo.* Also important was the competition in the media from other issues (e.g. Covid-19) or the nature of the big fires (for example, the availability of images, or the newsworthiness of the details, such as human casualties). However, as it shall discuss below, the "how" is here even more interesting than the "how many".

4.1 Fight and Resistance

Our hypothesis was confirmed. Over time, the resilience frame (in green, Fig. 2) has been taking a bigger piece of the media cake. It is worth mentioning that it was in 2021 when the resilience framework of wildfires accounted for more than one-quarter of all media stories (26%), despite having once been a very small percentage (8%). It is also noteworthy that the number of "Both-relevant" stories also peaked in 2021 (12%). Together, resilience and both-relevant frames gathered momentum at the end of the five years. In low-coverage years (2018 and 2020), fewer fires were covered from the perspective of suppression and no-framed stories were more important. This is consistent with the consideration that wildfires are a secondary, not a primary issue. The norm is that "more fires" leads to more coverage using the suppression frame.

Both the suppression and resilience frames articulate stories about "Fire damage", which include passages about hectares affected or people evacuated. Destruction and injuries, in this sense, are common ground in any story about wildfire. It is also worth noting that the resilience discourse does not adapt so easily to newspaper coverage of

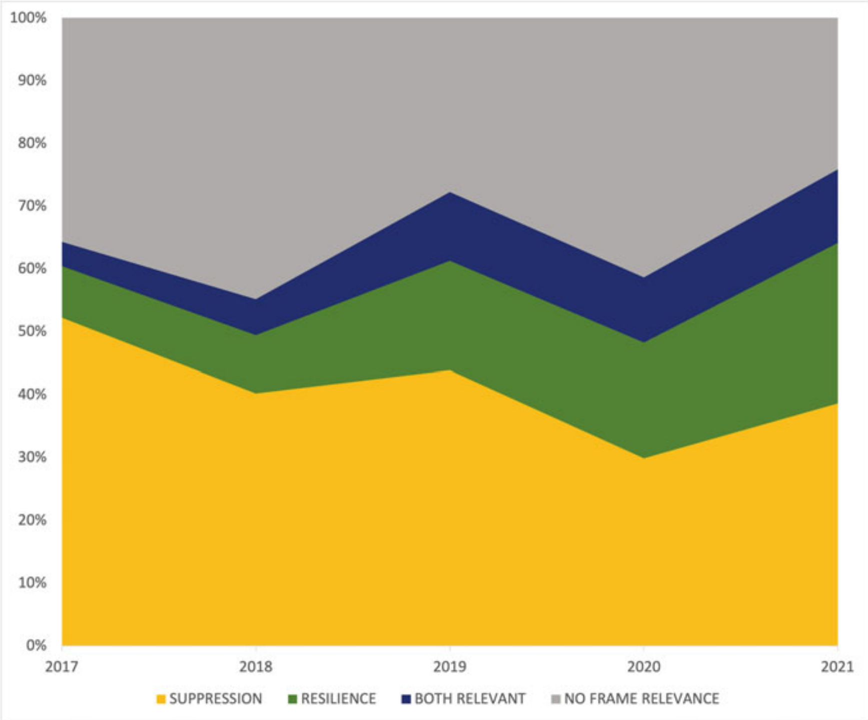

Fig. 2 Framing prevalence of wildfires 2017–2021 ($n = 656$)

fires. Resilience stories are demanding in terms of sources, length, and deep coverage, whilst suppression stories are already formatted, especially during the fire season. They can even be fitted to a sort of news template which provides common features such as fire location (where), affected zone (what), works of extinction (who and how) and, after some time, the cause (why). The stories are filled with official sources such as firefighters and risk official agencies (government, police, rural agents, etc.). Resilience, however, struggles to be formatted; it is a different media genre narrative and requires different sources such as experts and scientists. Resilience is a reflective frame, using concepts that people (and journalists) are still not used to. Therefore, it requires more experienced storytellers.

Figure 3 shows the sources of the suppression and resilience frames. For the first, the main marker and device is "Fighting and extinction". The language of these stories is filled with lexical choices belonging to the realm of war. The metaphor FIREFIGHTING IS A WAR is quite clear, although the specific term "war" is avoided and replaced by its language: "fighting" (*lucha*), "combat" (*combate*), "flank" (*flanco*), "attack" (*atacar),* "ammunition dump" (*polvorín*) are all commonly used. So we take for granted the army to fight this war; they are the firefighters and also the UME (Unidad Militar de Emergencias), a special corps of the Spanish Armed Forces that are frequently mobilized in the event of wildfires. When we examine the resilience frame, we notice a more complex system of lexical families. Data show that if the stories about fighting and extinction are dominant in the suppression frame, resilience stories tend to focus on the "Structural causation" of fires. Resilience is, above all, a story about the complexities of fires, their deeper causes, and how we should acknowledge and adapt to the reality that they are part of our environment.

The suppression frame has potentialities that are more connected with media logic and rationales. The focus on the spectacular nature of fires, drama or tragedy, criminal prosecution and firefighting challenges belong to the newscasting style. However, in

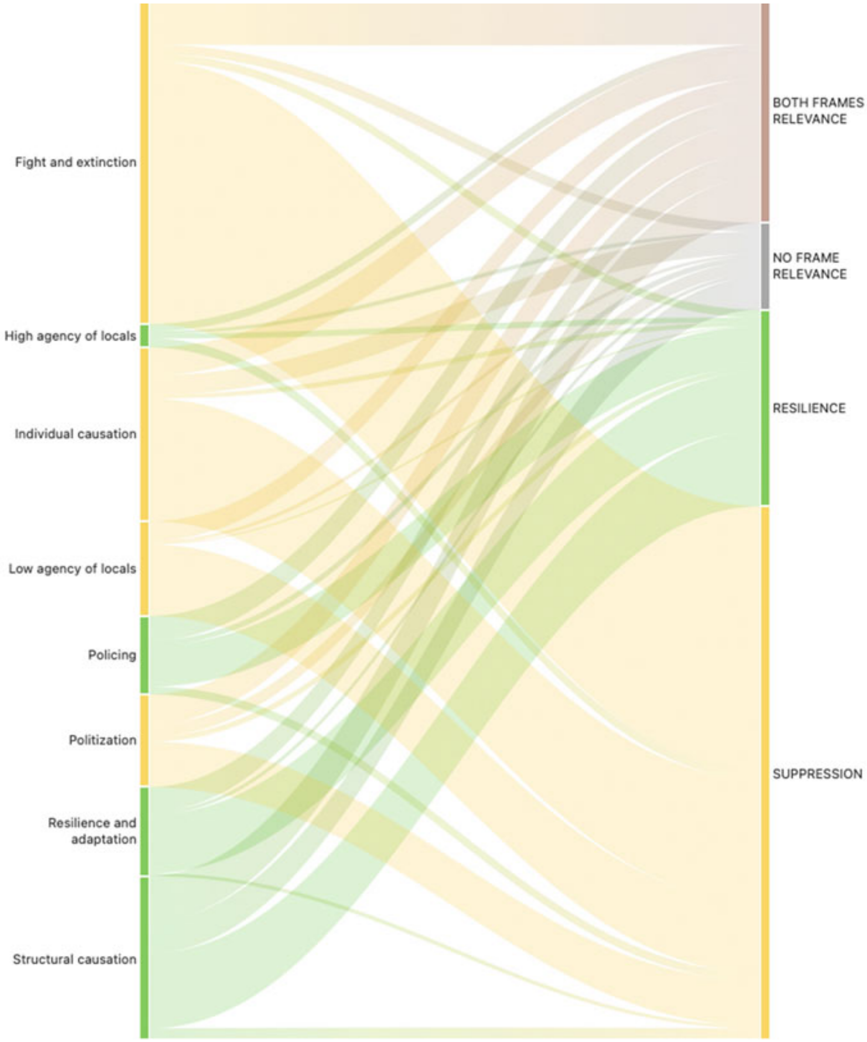

Fig. 3 Sources of frames 2017–2021

Fig. 4 Word cloud for the resilient frame pieces (only nouns, min occurrence = 40)

the corpus, we found examples of a different tone, in-depth reporting that focused on the more structural causation of wildfires, especially climate change. The cloud in Fig. 4 shows the words for the stories in the resilience frame (only nouns, minimum recurrence = 40). There are three or four that are specially worthy of comment. The first is *cambio* (change), the recurrence of which ($n = 195$) indicates that resilience is a narrative about changing, about transition. The name is attached to climate indeed, when we include nouns and adjectives, *climático* also appears very often (in Spanish, climate change means *cambio climático*). Concepts associated with climate change such as *temperatura* (temperature), *emisiones* (emissions) or *calentamiento* (warming) are evident here. Also worthy of comment is the importance of the word *gestión* (management). Its recurrence ($n = 76$) tells us that resilience is associated with some sort of human intervention and agency. The word is accompanied by others such as *personas* (people), *prevención* (prevention), *medidas* (measures), *situación* (situation) or *recursos* (means/resources). Resilience is about human agency and our ability to deal with situations surrounding fires. Finally, we point out the presence of the concepts like *extinción* (extinction), *area* (superficie), *hectáreas* (hectares) or *riesgo* (risk). This shows that resilience narratives are not opposed to firefighting, one of the findings of our research. Although the research aimed to confront the suppression and the resilience frames, there are many blurred, grey areas where both are articulated.

4.2 Policies and Agencies

Resilience narratives are about changing policies so that wildfires can be better contained before and after disasters occur. Newspapers did not pay enough attention to this issue during the period studied even though it was present, albeit only sporadically and in the technical sense, from the very beginning. In our corpus, the attempts to change policy were initiated by experts closely associated with firefighting. It was in the summer of 2017 and 2018, after the fires in Portugal and Greece, that people such as Marc Castellnou or Alejandro García (2018; Hernández, 2017) made important statements in *El País*. In their story, the paradox was clear: the more effort Spain made in terms of suppression, the more problems the country would face in the future. They both lamented that the authorities were investing in extinction, just when a new strategy was needed. Their discourse used the concept of resilience in its clearest form. However, the media only replicated this message reluctantly through the voice of experts or, very rarely, scientists. Since 2017, the resilience frame has been maturing its message, sometimes putting the focus on prescribed burns. Here, Marc Castellnou developed a metaphor that consisted of the analogy (LOW INTENSITY) FIRES ARE A VACCINE FOR MEGAFIRES (Carranco, 2017; Sáez, 2017). However, this readily understood rhetorical figure was not very successful in subsequent reporting, even when Covid-19 played havoc with journalism agendas in 2021. Although the analogy articulated the narrative of huge fires as an illness that could be treated with prescriptive fires (amongst other measures), it was still too advanced for the media focus on suppression.

This message contrasted with the still overwhelming presence of politicians talking after fires and promising aid for farmers and affected communities or a firm hand against the arsonists and criminals behind the fires. This was along the same lines as the suppression frame in which policies are seen as palliative and mostly associated with recovering from tragedy and loss. In this respect, the notion of financial aid is common. Affected communities claiming aid, or politicians going to the affected regions and discussing aid packages, were part of the suppression frame. This discourse had local communities playing the role of victims and, though demanding improvements, in a rather passive position. Here, the focus on the human drama, which is also triggered by the mediatization of wildfires, can activate human empathy in readers but not necessarily gives agency to the victims. The agency of locals is other of the unresolved aspects of the resilience frame. In the discourse of suppression, it is very clear: locals are affected, and they are evacuated, helped, and must be protected. However, it would be desirable and expected to notice greater agency in the resilience frame and read stories of communities preparing their properties, organizing meetings with policymakers and explaining how they protect themselves (or authorities promoting this). These elements are almost completely unnoticed in the stories. The agency of the local people needs to be further developed in the future of the resilience frame storytelling. Surprisingly, the suppression frame appropriated this gap and colonized the device of high agency of locals. Although coloured green (Fig. 3), it is the weaker element but added more to suppression than to resilience. This is because we find stories about locals helping to extinguish fires by fighting against them. To date, the suppression discourse has a major role reserved for communities: contributing to "the fight" when "the enemy" is at their door.

As well as this, some stories include the theme of rural depopulation, but this is usually articulated by experts or politicians. In the study, this issue was included under the framing device of structural causation. However, we noted that it is not a claim from the grassroots that evidences empowerment from the communities. Sometimes "the rural" is even used politically and vindicated by all parts of the ideological spectrum. All these aspects reveal that resilience building is a political matter, part of the realm of "policies", whilst suppression is part of the "politization" of wildfires (political blaming, political statements after disasters, political promises of aid, disqualifications and counterstatements, etc.). Paradoxically, this sort of media politization, which is part and consequence of mediatization processes, depoliticizes wildfires.

4.3 Elements of Mediatization

The resilience frame gained momentum during the period analysed thanks to the process of wildfire mediatization. From the "mediatized sources" involved in wildfire communication, we made a list of the agents who were profiling the frame throughout the analysed period. Some of the sources are from the emergency services (fire-fighting bodies, civil protection). These, and local people closer to affected areas, are promoters of the suppression frame. But for the resilience frame, we tagged other sorts of sources, such as experts and scientists, institutions, and universities, some of which are specialized centres or sections of official bodies. There was some correlation between the presence of these sources and the presence of the resilience frame: they use a certain type of language, articulate particular arguments and offer complexities and background. This is a salient result that explains why resilience stories are gaining space within the media: there is a greater presence of specialized sources replicating a different discourse. Also, this would problematize the idea that resilience is a narrative coming from the grassroots, it is not (at least in the media), but this is a matter that I do not have space to properly discuss here.

More sources of this type would lead us to expect still more stories within the resilience frame. And this is a challenge: the resilience frame does not readily adapt to media logic and mediatization processes. As said, suppression stories are about emergency, action and drama: they tell of firefighters attacking the front, people having to leave their homes and authorities sending more forces. The information and drama fit the media requirements perfectly. However, explanations from experts and scientists are of a different ilk. They need to be modelled and adapted. Mediatization of experts and technical staff could have a better role in wildfire stories when deployed at the right time, delivered within attractive formats and pictures and used easy-to-read metaphor and language. However, the process can also lead to simplification. These ideas are connected with Plana's (2011) consideration of the challenges that experts face to connect with non-specialized publics and the media. Ultimately, they present a cross-current narrative: they try to explain that extinction is not so effective, and they adopt discourses on "good fires" and focus not on flames but on soils, not on the evil arsonists but on the lonely farmer, not on the villagers tragedy but on rural abandonment and policies. Resilience stories are anti-climax almost by default. There is a huge task here: resilience stories are not "sexy" enough, so far, for high mediatized stories in networked times.

One of the tasks to do is to transform risk stories. Risk was tagged as a neutral element; it is a wild device. It was often found as part of the discourse of prevention;

all stories can appropriate risk. Under a functionalist perspective, media are tools for social risk awareness. The media play the role, and stories of risk are attached to both the suppression and resilience frames. They are especially active during heat waves, when the media replicate the warnings coming from the authorities, and when they inform about restrictions and even prohibitions on accessing certain areas. Thus, the risk is related to climate change and, in some stories, is a consequence of structural causalities (heat, the density of fuels, drought, firework displays, etc.).[4] Risk is however a multifaceted frame, a sort of joker card, and media should rethink their role in mixing risk, drama and suppression stories and explore how to better articulate stories in which risk is linked to collective responsibility, effective policies and social response to fires.

5 Discussion and Conclusions

This research shows that the resilience discourse on wildfires in Spain is growing. Like all research, it has limitations. The most evident is that the analysis used a dichotomized structure within the media framing approach. It also focuses on written journalism and did not attempt to analyse visuals, despite the role they play in framing stories. Even so, it accomplished its objectives. Suppression and resilience frames are not opposed. They both use some of the frame devices that we labelled as neutral, for example, fire damage (material, environmental or human) or risk. The results are also in tune with advances in media wildfire framing, and we noted that the approach depended on the "disaster timeline" ("frame changing") (Crow et al., 2017a, 2017b; Houston et al., 2012). We could even mention that the suppression frame is closer to what the framing literature refers to as an episodic frame (Gamson et al., 1992; Iyengar, 1991), in our case, attached to the fire season.

How the media explain fires is undergoing an important change because of super-fires, or "6th generation" fires, a concept that emerged during the five years of the study. The resilience frame is a complex and reflective frame that is gaining momentum in the media, partially thanks to a process of mediatization. Part of this process has an impact on the sort of information sources that the media are using. Most of them are still official sources, as it was stated by previous research (Fabra-Crespo & Rojas-Briales, 2015; Vicente-Mariño & Delgado-Arango, 2019), and replicate suppression frames. But now, new, more specialized agents are taking their place in the Spanish media, with a different story to tell, putting the accent on resilience and technical aspects. In our study, we also identified opportunities for improvement around the agency of rural and local communities. The media should pay more attention to the role of farmers and villagers, to the structural elements of the rural contexts and its challenges (e.g. depopulation, agri-food model), as well as

[4] Here, it is worth mentioning that in Catalonia, it is a custom to set off fireworks on Saint John's night to celebrate the summer solstice. *La Vanguardia,* a leading newspaper in the region, emphasizes the risk almost every year to some extent or another.

to the measures to take in the territory to, as Castellnou said, “vaccinate” it against superfires. Here, we propose a rural scope on news, reports and media storytelling on wildfires.

The resilience frame must overcome many challenges if it is to become more preeminent in the media, but it is difficult to predict how the discourse is going to evolve. However, one scenario is that the global warming indicators will strength its establishment and even promote its hegemony. In the field of wildfires, both resilience and suppression are being reactivated. They do not oppose each other; they feed off each other and evolve. Therefore, it is not a process of substitution. Moreover, although mainstream media are limited in terms of space, there are numerous other places in the networks and social media that are ready and waiting for more content about wildfires, new understandings and stories. Although perhaps less influential, they should not be underestimated.

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Fire Severity as a Determinant of the Socioeconomic Impact of Wildfires

E. Marcos, J. M. Fernández-Guisuraga, V. Fernández-García, A. Fernández-Manso, C. Quintano, S. Suárez-Seoane, and L. Calvo

Abstract Fire has played a crucial role in shaping Earth's landscapes for millions of years and has been used as a cultural tool for human development for millennia. However, changing fire regimes driven by global change drivers and human influences are reshaping landscapes and leading to more severe wildfires, with significant socioeconomic and environmental consequences. These wildfires have substantial direct impacts on human lives, properties, and mental health, as well as indirect impacts on ecosystem services, negatively affecting provisioning, regulating, and cultural services. In general, severe wildfires disrupt the functioning of ecosystems and the subsequent recovery of the ecosystems services. Remote sensing techniques represent efficient tools for monitoring post-fire ecosystem service recovery. On the other hand, the impact of large fires is perceived differently by society influenced by socioeconomic factors, previous experiences, and community dynamics. Understanding these perceptions is essential for developing effective wildfire management and mitigation strategies at the local level. To address the challenges posed

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by changing fire regimes, a Fire Smart Territory (FST) approach could be considered, emphasizing integrated fire management that considers prevention, effective response, and post-fire restoration. This approach presented in this book chapter also promotes the involvement of local communities in fire prevention and management. So, the conservation of ecosystem services in fire-prone areas requires a holistic and adaptive approach that incorporates ecological knowledge, societal needs, and sustainable land management practices. By adopting an FST framework and considering the complex interactions between fire, ecosystems, and human communities, it is possible to mitigate the impacts of wildfires and promote resilience in these vulnerable landscapes.

Keywords Ecosystems services · Fire regime · Fire smart territory · Post-fire management · Remote sensing methodologies · Social perception

1 Introduction

Fire is a key environmental disturbance that has shaped biomes since 400–350 million years ago across most of Earth's land surface (He et al., 2015). Specifically, for more than 9000 years, fire has been used as a management cultural tool targeted to the opening and maintenance of pastures and croplands, thus largely contributing to human development (Carracedo et al., 2018). Nevertheless, during the last decades, historical fire regimes are shifting due to multiple interactions among global change drivers (mainly climate and land use change) and due to direct human influences, such as ignition and suppression (Rogers et al., 2020). Complex socioeconomic changes (i.e., rural depopulation, land abandonment, or proliferation of rapid-growing forest plantations) have imposed shifts in fuel amount and connectedness (due to massive woodland and shrubland increases in the European countries of the Mediterranean Basin) across traditional landscape mosaics (Delgado-Artés et al., 2022). This landscape homogenization, occurring in a context of climate change (i.e., warmer and drier conditions), is driving a significant change in wildfire typology from small, fuel-limited fires to drought-driven fires (Chergui et al., 2018).

In global terms, it has been noticed an increase in the number of mega-fires and extreme wildfire events that are strongly severe, such as those that occurred in 2017 in Portugal (Turco et al., 2019), in 2020 in California (Higuera & Abatzoglou, 2021) and, recently, in 2022 in Spain. Indeed, the frequency of heat-induced fire weather is projected to increase by 14–30% by the end of the century (2071–2100) depending on the climate change scenario, being suggested that the frequency and extent of large wildfires will increase even more throughout the Mediterranean (Ruffault et al., 2020) and the Boreal region (Drobyshev et al., 2021). The higher the warming level is, the larger the expected increase of burned area, ranging from 40 to 100% across the IPCC scenarios, with significant benefits if warming is limited below 2 °C (Turco et al., 2018).

These new patterns of fire regime are generating multiple (economic, social, and environmental) impacts on society that are driving extraordinary damages (Thomas et al., 2017), increasing direct risks on human lives, and also on good provision and poverty (Paudel et al., 2021), particularly at the wildland–urban interface (Radeloff et al., 2018; Rosenthal et al., 2021). The main impacts of these severe wildfires on society are direct such as human losses, damage to homes and other infrastructures and physical and mental health (Rosenthal et al., 2021). In addition to direct impacts on people and economic losses, severe wildfires also have other substantial effects on society through indirect impact as the alterations of the ecosystem services, defined in the Millennium Ecosystem Assessment (MEA, 2005) as "conditions and processes through which natural ecosystems sustain and fulfil human life".

Wildfires are highlighted as one of the major disturbances that negatively trigger ecosystem services. In this context, some studies (Taboada et al., 2021) have demonstrated these negative effects on the provisioning services in a fire-prone landscape dominated by pine forests, because they interrupted the capacity of providing timber, mushroom, firewood, and animal hunting, all of them very relevant for the local rural economy of the surrounding areas. Furthermore, wildfires affect negatively most of the regulating services due to the effects on soil erosion, runoff, water quality, and soil fertility, among others (Roces-Díaz et al., 2022). Finally, cultural services, such as cultural heritage and recreation are also negatively affected (Roselló et al., 2020). However, the negative effects on ecosystem services will depend on the type of vegetation affected and their adaptations to recover easily after a fire since in areas dominated by species with fast regeneration some services may be favored, but always depending on the fire severity. Mola & Williams (2018) reported a positive influence of a low severe fire affecting shrublands and grasslands by the creation of open landscapes with an increase in the floral density that represents a more favorable environment for pollinators' net. Therefore, fire severity is one of the main constraints of the effects of forest fires on the provision of ecosystem services to society.

2 Impacts of Fire Severity of Large Wildfires on Ecosystem Services

Comprehensive analysis of the socioeconomic impacts of large wildfires is often addressed through the ecosystem services approach. These wildfire impacts have been studied across the globe (Roces-Díaz et al., 2021), revealing both positive and negative effects depending on the type of service assessed (provisioning, regulating, and cultural), and the type of ecosystems and society in terms of development (Pausas & Keeley, 2019; Pereira et al., 2021; Roces-Díaz et al., 2021). However, the impacts of fire severity on ecosystem services are less known. The fire severity impacts are the result of immediate impacts on ecosystems and biogeochemical cycles, and of indirect influences on post-fire recovery (Huerta et al., 2022). Concerning the immediate impacts, fire severity is inherently linked to a different degree of vegetation consumption and mortality (Keeley, 2009), to a different magnitude of change in litter and soil properties (Fernández-García et al., 2019), and affections to fauna (Jager et al., 2021). This unavoidably extends to the inter-relationships of all these elements, as well as to ecosystem structure and processes. Focusing on ecosystem responses, fire severity shapes vegetation recovery, as plants have differential responses depending on their functional traits, ones being favored by severe fires (i.e., some herbaceous, and many shrub species with adaptative traits) while others temporarily decline (usually arboreal vegetation) (Fernández-García et al., 2020). Similarly, fire severity influences the post-fire trajectories of soil properties in different ways (Fernández-García et al., 2019). Pioneer work in heterogeneous mountainous landscapes (Huerta et al., 2022) has shown how several ecosystem services and related functions change in function of fire severity one year after the fire (Fig. 1). The analysis revealed decreases in the supporting service proportional to fire severity, a consequence of the loss of photosynthetic activity, nutrient cycling capacity, and soil quality. An increase in the provisioning service was found after low-severity burning and a decrease in severely burned areas, in response to analogous shifts in grass production for livestock and wood production. The regulating service decreased proportionally to fire severity, as it caused significant decreases in carbon stocks and erosion protection. The cultural service, studied through the woody species diversity and aesthetic value (diversity of floral colors of woody species), decayed mainly at moderate severities. Among the studied functions, only soil fertility increased proportionally to fire severity. These results are in line with those reported in previous studies comparing prescribed fires (usually less severe) and wildfires (usually more severe) (Fig. 1) (Pereira et al., 2021; Roces-Díaz et al., 2021), suggesting similar underlying mechanisms. Despite the foregoing, further work is necessary to achieve a better understanding of the complexity of fire severity's influence on ecosystem services, as multiple environmental site-dependent factors might intervene (Fernández-Anez et al., 2021).

3 Ecosystem Services Recovery After Large Wildfires: A New Methodological Approach

Current and predicted fire regime shifts in the Mediterranean Basin may harm the high resilience to fire that fire-prone Mediterranean ecosystems have exhibited under historical fire disturbance regimes. In this context, the natural recovery of ecosystem functions and services provided by these ecosystems could be endangered by unprecedented fire impacts on the soil and vegetation, as well as by transitions to alternate stable ecosystem states (Johnstone et al., 2016). Therefore, the assessment of how the functional indicators of ecosystem functions and services recover to a pre-disturbance state is essential for supporting adaptive management strategies to safeguard the ecosystem services' flow for human well-being worldwide, especially in the most vulnerable regions.

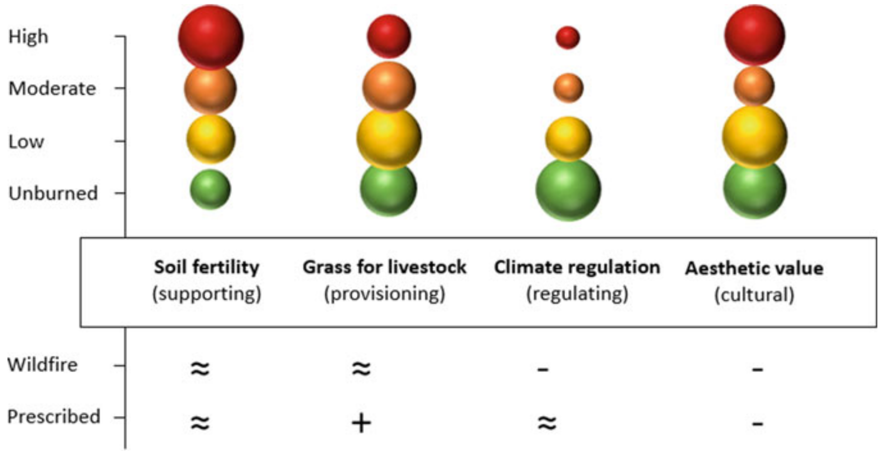

Fig. 1 Influence of burn severity on four ecosystem functions or services, each one included in a different major group of ecosystem services is shown in the upper part, with balloon sizes proportional to the service provision. The influence of prescribed burning and wildfires on these services is shown in the lower part. Based on Pereira et al. (2021), Roces-Díaz et al. (2021), Huerta et al. (2022)

Field-based inventories have been traditionally used to measure soil and vegetation functional indicators as proxies of the recovery of ecosystem functions and services with high reliability. However, in the context of global change, with increasingly large burned areas encompassing several plant communities, this approach is no longer versatile. Field inventories may not capture the total ground spatial heterogeneity in large, heterogeneous burned areas and do not allow wall-to-wall (i.e., spatially explicit) estimates. In this sense, the synoptic nature of active and passive remote sensing earth observations, in combination with precise field measurements, offers nowadays an efficient way to achieve this goal.

Conventionally, open data from multispectral passive optical sensors have been used to estimate supporting services' recovery, mainly ecosystem productivity. For instance, McMichael et al. (2004) applied a normalized difference vegetation index (NDVI)–leaf area index (LAI) model using multi-temporal Landsat data to estimate LAI in a chronosequence approach as a proxy of ecosystem productivity recovery in chaparral shrublands in central California. The temporal dynamics of ecosystem productivity in burned sagebrush communities of the western United States were examined through a dynamic global vegetation model and the gross primary production product from MODIS (Pandit et al., 2021). Fernández-Guisuraga et al. (2022a) proposed the use of physical-based approaches (radiative transfer and pixel unmixing models) for retrieving fractional vegetation cover from a pre- and post-fire time series of Sentinel-2 data as a vegetation productivity resilience metric in several forest and shrubland communities in the western Mediterranean Basin.

Passive optical reflectance data is related to the general trends in the recovery of ecosystem services related to the top-of-canopy vegetation traits in multilayered

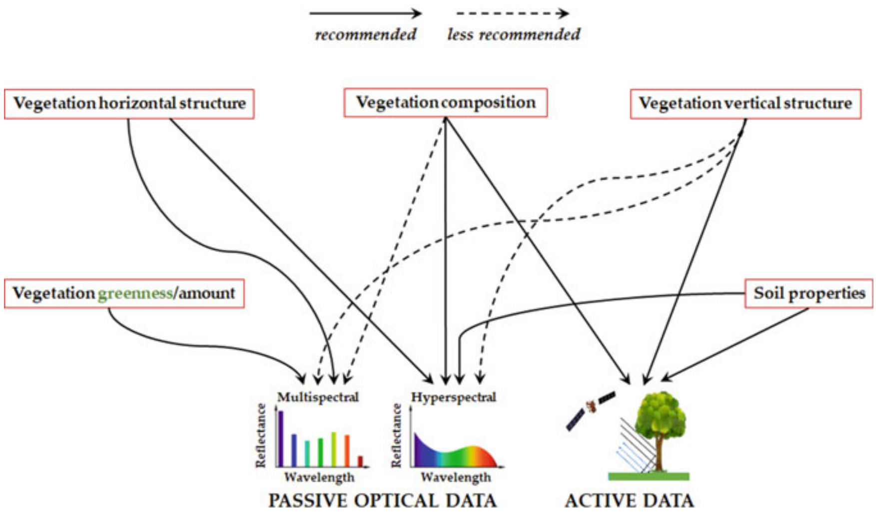

Fig. 2 Appropriate remote sensing products for the assessment of several ecological variables

plant communities (Fig. 2) such as ecosystem productivity. The recovery assessment of other ecosystem services closely related to the vertical profile of the vegetation structure (e.g., aboveground carbon stocks and wildlife habitat), or to the soil properties, requires the implementation of active remote sensing techniques (Fig. 2), or fusion approaches with passive data.

The sensitivity to the quantity and distribution of vegetation scatterers throughout the canopy of light detection and ranging (LiDAR) and synthetic aperture radar (SAR) sensors has been exploited to evaluate the ecosystem services of the recovery of aboveground carbon stocks (Fernández-Guisuraga et al., 2022b) and structural complexity for wildlife habitat (Fernández-Guisuraga et al., 2022c) in Mediterranean fire-prone plant communities worldwide. Regarding the ecosystem services supported by the soil, Fernández-Guisuraga et al. (2022d) leveraged the increased interaction of SAR backscatter data in the L-bandwidth with soil surface properties for retrieving soil organic carbon and nutrients content as proxies for post-fire recovery of belowground carbon stocks and nutrient cycling services. Although LiDAR and SAR data have the potential to monitor other types of ecosystem services such as timber production (Yoga et al., 2018) or edible fungi production (Peura et al., 2016), to date these methods have not been applied to the assessment of ecosystem services recovery after fire.

The remote sensing-based research presented above has provided a sound methodological basis and reliable results on the recovery trends of specific ecosystem services after different scenarios of fire severity, which also allowed the estimation of their driving factors regarding the fire regime, the dominant vegetation life-history traits, and the environmental conditions in Mediterranean landscapes. These studies evidenced that plant communities dominated by resprouting species exhibit an enhanced recovery of ecosystem services such as ecosystem primary production, habitat structural diversity, and aboveground carbon stocks in the short term after a fire, as compared to communities dominated by obligate seeders. Likewise, fire severity undermines ecosystem services recovery by affecting both resprouting and seeding capability of the dominant species in the communities, but the magnitude of this effect seems to be modulated by environmental resource availability. Enhancing the resilience of ecosystem services provided through the promotion of resprouter species and the implementation of adaptive management strategies to prevent high fire severity burnings should be a priority in Mediterranean fire-prone landscapes.

4 Social Perception of the Impact of Large Wildfires

In the last few decades, the greater occurrence of large and destructive wildfires leads to an increase in the impact on social systems. Although in most studies this impact is measured in terms of economic losses (e.g., home loss or suppression costs), significant research has been developed on the human dimensions of wildland fire since 2000 (McCaffrey et al., 2013), by addressing topics such as social dynamic change after a wildfire, public response during fires, or attitudes toward implementation of forest fire mitigation measures (McCaffrey et al., 2013; Paveglio et al., 2015). These studies were carried out through surveys of the population, workers and volunteers in medical facilities, social services agencies, and non-profit organizations located in communities affected by wildfires (Rosenthal et al., 2021).

Social perception of wildfires can be shaped by their previous experiences, people's standard of life, their interaction with land and forests, and their worldviews. For instance, Yulania et al. (2021) found that the inhabitants of rural areas of Indonesia had a perception that usual practices of burning forest and land will be detrimental to their society, so their participation and supervision of forest and land use would be fundamental to manage the environment properly. Other populations in the northwest of Spain have a similar perception of the damage of wildfires both for the ecosystem and for the people living in these areas. In this case, they attribute the responsibility to mitigate the fire damage to the local and regional authorities but did not perceive a social co-responsibility in this problem (García-Mira et al., 2008), because they consider that wildfires are caused by criminal behavior. A different perception was found in a study following the largest wildfire that occurred in Sweden in 2014 (Lidkogs et al., 2019). The population did not blame forestry companies or fire departments, rather they considered this disaster as a learning opportunity to improve the prevention of future events and to create a nature reserve with positive consequences (higher biodiversity). However, people's perceptions change when, in addition to living in areas affected by frequent fires, they live under poverty conditions, and overcrowded and structural issues, such as what happens in some areas of Chile. In such a context, people perceived that authorities were not concerned about the risk, and so, they felt very vulnerable to the occurrence of a disaster caused by wildfires. Sapiains et al. (2020) recommended that in these situations local communities should have responsibilities to improve the negative perception of themselves and should create more social interactions. After destructive fires in California, Rosenthal et al. (2021) found that wildfire survivors perceived (i) accessing safe and secure shelter mainly for those whose homes were lost; (ii) the economic instability which increases anxiety or depression; and, (iii) mental and emotional well-being and access to health resources as the main social problems. Participants in this survey pointed out the deficiency of private and public recovery resources used to restabilize following the fire, and therefore, the administrations should implement structural changes to cover the needs of wildfire survivors.

The studies mentioned above showed the variability in the social perception of the impacts of large forest fires, which implies that the solutions to mitigate this problem are complex. Further study and new methodologies for its assessment are needed to understand the social consequences at the local level (Paveglio et al., 2015). Future research could help to strengthen the role of the community in designing and implementing preventive measures together with governmental agencies.

5 Management and Conservation of Ecosystem Services in Fire-Prone Areas

Despite the intense efforts dedicated to forest fire suppression in western countries, the challenge of reducing the impact on ecosystem services is far from being solved. Current forest fire policies in these countries have not solved the problem, and probably they will not be effective in the future, as all initiatives focus on fire suppression and minimize the traditional use of fire based on the ecological knowledge of former European communities. This traditional use of fire as a tool for land management has been manipulated and almost criminalized by an urban-centric perspective and an anti-fire bias (Tedim et al., 2016).

From an anthropogenic, technological, and ecological approach, the most "holistic" concept is the so-called "Fire Smart Territory" (FST), which puts at the center of the problem the "territory" understood in a broad sense, not only as landscape but as the social and psychological interpretation of the landscape. The fundamental assumptions of FST are that fire is a dual and ambiguous process, and that it is not simply a biophysical process with social connotations but a social process. It is a complex issue that can be understood only in coupled human and natural systems. The local understanding of the wildfire problem prepares strategically each territory to make it less prone to wildfire and its inhabitants less vulnerable and more resilient, in the scope of economic valorization, sustainable development, and security of the territory's resources.

We have designed a new model, based on a triad or group of three factors especially linked to each other, to carry out an integral and coherent management of forest fires within the framework of ecosystem services conservation (Fig. 3). This figure depicts

Fig. 3 Triangle defining management strategies and conservation of ecosystem services in fire-prone areas in Fire Smart Territories (FST)

the triangle that serves to define an FST and expresses the interaction among risk management in mosaic landscapes (prevention), the effective response when a fire occurs, and the post-fire restoration supported by proven ecological knowledge.

In this sense, strategic thinking and planning that FST posits must recognize and accept fire as a natural process necessary for the maintenance of many ecosystems and strive to reduce conflicts between fire-prone landscapes and people. Thus, Integrated Fire Management implies a greater integration of the different components of fire management (prevention, detection, suppression, and use).

The first question to be asked when the goal is to create an FST is: how to design fire prevention in fire-prone agroforestry landscapes? As indicated above, the socioeconomic change in land uses has created a continuity of wooded forest stands together with high fuel accumulation that could favor the occurrence of large wildfires, with crown fires and massive secondary outbreaks. In this sense, fire prevention and suppression approaches that have relied exclusively on silvicultural measures and containment infrastructures are increasingly ineffective in stopping the spread of wildfires. Given that agroforestry landscape mosaics composed of a mix of different land cover and land use types are considered less prone to fire than forests, approaches that support the involvement of rural people in agricultural and forestry activities should be proposed (Bertomeu et al., 2022).

This preventive management model aims to defend the vulnerability of ecosystem services, i.e., the physical, social, economic, and environmental factors that increase the susceptibility of individuals, communities, settlements/buildings, ecosystems or systems to damage, and loss from wildfires. This model contributes to increasing the effectiveness of resistance (reducing fire severity to give trees a chance to survive) and promotes resilience (post-fire rehabilitation and landscape diversification to give vegetation a chance to regenerate in case of future fires). Marino et al. (2014) carried out a quantitative Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis applied to Spain to analyze fuel management for forest fire prevention. The study highlighted how solutions to forest fires should be based on rural development that includes sustainable forest management and an integrated defense against fires. The impulse of the public administration with active policies that allow taking advantage of these opportunities is proposed as a priority if the challenge of reducing the severity of forest fires in the context of climate and socioeconomic change is to be faced with guarantees.

As a complement to risk management in mosaic landscapes, Madrigal et al. (2019) proposed the creation of Strategic Management Zones, areas of the territory defined and prioritized according to a specific methodology that, taking into account the fire risk, the fire behavior in the study area and the vulnerability of its natural, rural, or urban values to be protected, allows to establish and optimize space-temporal planning of fuels and infrastructures that limits the fire potential, detecting extinction opportunities, and anticipating an effective and safe defense strategy for large forest fires type for which it has been designed.

The second key question related to the creation of an FST is: what should be the fire suppression approach to avoid the wildfire paradox? To answer this question we have followed the approach taken by projects such as "Fire Paradox" (Silva et al., 2010) which is based on the paradox that fire can be "a bad master but a good servant", so it is necessary to take into account the negative impacts of current wildfire regimes (understanding initiation and spread) and the beneficial impacts of controlled fires in vegetation management and as a planned mitigation practice (prescribed burning along with some traditional fire uses) and for fighting wildfires (suppression fire).

Faced with the challenge of climate change, this second FST strategy proposes to take an unbiased view on the value of both the use of fire to mitigate risks—through prescribed, indigenous, and controlled burning—and to allow some wildfires considered to be low risk to run their natural course. This path also requires identifying the most at-risk ecosystems from large and severe wildfires and prioritizing mitigation measures to balance their impacts.

Finally, the third and last question is: how to deal with post-fire restoration when the first two strategies have not worked? According to the Spanish National Ecosystem Assessment (SNEA), in Spain, 45% of the ecosystem services assessed have been degraded or are being used unsustainably, with regulating services being the most affected. One of the main drivers of degradation has been large, high-severe wildfires.

6 Conclusions and Final Remarks

Post-fire restoration aims to mitigate or reverse the negative ecological and socioeconomic impacts of fire. These impacts are related to the fire regime and its interactions with ecosystem resilience to fire. In the case of severe fire regimes, the main environmental impacts affect nutrient balance, soil erosion risk, and biodiversity reduction. Post-fire restoration planning requires the identification of specific fire-triggered degradation processes, including their temporal and spatial dimensions, and vulnerable ecosystems. Restoration should address the identified vulnerable areas and mitigate the risk of soil erosion and runoff in the short term, as well as the recovery of nutrient cycling and key plant species in the long term (Vallejo & Alloza, 2015).

An important decision in post-burn forest management, when restoration of the old forest type is the primary objective, is whether to use natural regeneration (indirect restoration), if present or expected to occur, or active restoration (plantings and seeding). Depending on the objectives, this may involve thinning, shoot selection, and control of unwanted vegetation. The costs associated with assisted natural regeneration can be much lower compared to active restoration, meaning that a much larger area can be effectively treated with a similar amount of available funds. Of course, the decision of active *versus* natural restoration will be conditioned by vegetation type, ecosystem response, burned area objectives (Mola et al., 2018), and the societal needs of these burned landscapes.

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Forest Ecosystems, Forest Fire Internet of Things (FFIoT), and Socioeconomic Aspects

Asimina Skouteri, Konstantinos Spanos, Peristera Kourakli, and Panagiotis Koulelis

Abstract Forests play a significant role in any circular economy strategy aimed at achieving sustainable development, human well-being, and national welfare. Forest fires are responsible for substantial losses in forest ecosystems and the valuable ecosystem services they provide. The Internet of Things (IoT) constitutes a collaborative ecosystem comprising smart devices, networking infrastructure, and advanced processing technologies that work together to create smart environments for end-users. This revolutionary technology ensures continuous access to information and facilitates the integration of people and data, contributing to a greener future. It offers effective methods and substantial technical support for forest and environmental sciences and sustainable forest planning and management. Despite the transformative impact of technology in various sectors, the forestry industry has been slow to embrace digital technologies. IoT can be effectively designed and implemented across all phases of forest fire management, transitioning it from a manual system to a digital one with widespread remote participation and governance. This transformation results in the development of more resilient forest landscapes in the face of climate change and external disasters. Achieving a consensus on measures, including hardware, software, and skill requirements, is crucial for ensuring effective information provision. Additional research methods and approaches are needed to address emerging economic, environmental, and social challenges, and there must be a general agreement on what aspects to measure and how to measure them.

Keywords Internet of Things (IoT) · Forest fires · Sustainable development · Resilient landscapes

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1 Introduction

Historically, the concept of IoT has its roots in the ancient Beacon Tower system. This system was employed in China and other countries to rapidly warn about unexpected fires on hills or towers as an early alert for potential enemy invasions (Zhao et al., 2013). IoT is an emerging and innovative technology, and many definitions and frameworks have been studied, analyzed, developed, and proposed. Generally, the architecture framework of IoT includes four key layers: (a) a device layer, (b) a network layer, (c) a data analytics layer, and (d) an application layer (Sahal et al., 2021; Singh et al., 2021). IoT-based technologies find applications in various aspects and areas of life and science (Maksimovic, 2018; Nižetić et al., 2020). The primary objective of this revolutionary technology is to enhance the quality of life by transforming processes in different fields. Figure 1 illustrates the main IoT-related applications related to forest topics.

According to the Food and Agriculture Organization (FAO), a forest is defined as "a land area of more than 0.5 ha, with a tree canopy cover of more than 10%, which is not primarily used for agricultural or other non-specific non-forest purposes" (Foundation, C.D.R., 2020). As of 2016, the total global forest area was estimated at 39,958,245.9 km^2 (Forest Area, 2022).

Forests are recognized as dynamic providers of ecosystem services (Spanos et al., 2021), and any significant disruption to their existing structure can have various impacts on different aspects of human well-being. Forest fires, along with insect infestations and forestland fragmentation, are among the major causes of unsustainability. Conventional forest fire management (FFM) often lacks coherence and efficiency, hindering the development of an integrated approach and complicating decision-making processes, resulting in the inefficient use of human and material resources. The primary objectives of integrated FFM are twofold: (a) to minimize the damage caused by unintentional fires and (b) to maximize the benefits of intentional, prescribed fires (Nyongesa & Vacik, 2018). Prescribed fires offer several positive effects, such as controlling insect pests, reducing competition for nutrients,

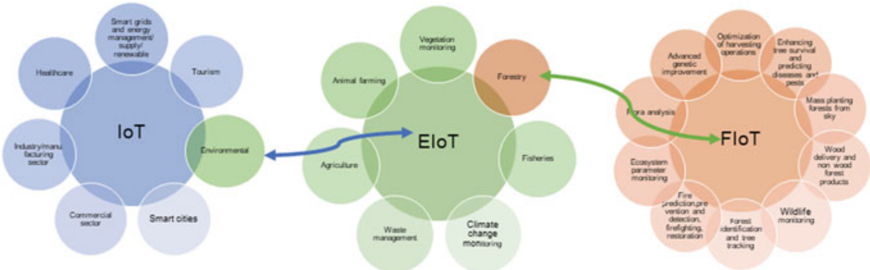

Fig. 1 Applications of Internet of Things (IoT), Environmental Internet of Things (EIoT) and Forest Internet of Things (FIoT) (Asghari et al., 2019; Bayne et al., 2017; Bo & Wang, 2011; Choudhry & O'Kelly, 2018; Hock et al., 2016; Li et al., 2019; Zhao et al., 2005)

and providing habitats for nesting birds, making them an integral component of FFM due to the ecological benefits that often outweigh their negative effects.

It is widely acknowledged that an integrated, sustainable, human-centered, and proactive approach to FFM should address the root causes of extreme forest fires (wildfires) (Wunder et al., 2021). Many international initiatives have been launched in relation to forest land restoration, which are highly connected with the main goals of an IoT ecosystem:

- The Bonn Challenges aim to bring 150 million ha of degraded and deforested landscape into restoration by 2022 and 350 million ha by 2030 following the global agenda for sustainable development.
- New European Union (EU) Forest Strategy for 2030 recognizes the crucial and catalytic role of forests in making Europe the first neutral continent by 2050.
- The EU Biodiversity Strategy for 2030 sets out a pledge to plant at least 3 billion additional trees by 2030 following the ecological principles (right tree in right place and for right purpose).

IoT is a new technology around the globe and has the potential to contribute to socially and ecologically sustainable forestry. Regarding the agriculture sector, the social impacts and inequalities linked to digital agriculture need to become a key concern of policy makers so that the above-mentioned potential will be determined (Hackfort, 2021). Agriculture is undergoing high transformation due to the technological assets. On the other hand, forestry is running behind the majority of the industries that have already adopted that practice (Choudhry & O'Kelly, 2018). This has recently started to change. In forestry, digital technologies confront a system which has been established for a long time—76% of forests globally are public-owned with the remainder being held by holders of average less than one-hectare land. Management of state or public forests is usually conservative and private forests lack scale and expertise needed for adoption of new technologies (Choudhry & O'Kelly, 2018). Forest Internet of Things (FIoT) is a category of IoT and refers to smart devices distributed in forests mainly for monitoring, management, fire detection, and prevention (Sahal et al., 2021).

Figure 2 illustrates an FFM framework that highlights the primary facets and associated activities (pre-, at-, and post-fire management) where IoT can serve as a valuable tool. Numerous suggestions emphasize the urgent need for a digital forest system. Choudhry and O'Kelly (2018) have emphasized that there is no time to waste, and action should begin immediately, rather than waiting for technology to fully mature. Therefore, it is imperative to develop a roadmap by initiating small-scale projects initially and subsequently expanding them on a larger scale. However, it is important to consider a structure that can mitigate operational and financial risks. Additionally, Nassef (2022), a leading figure in climate adoption policy at the United Nations, noted in an interview that the substantial transformation of our actions over the next decade, including the adoption of digital technologies, is crucial to preventing human extinction.

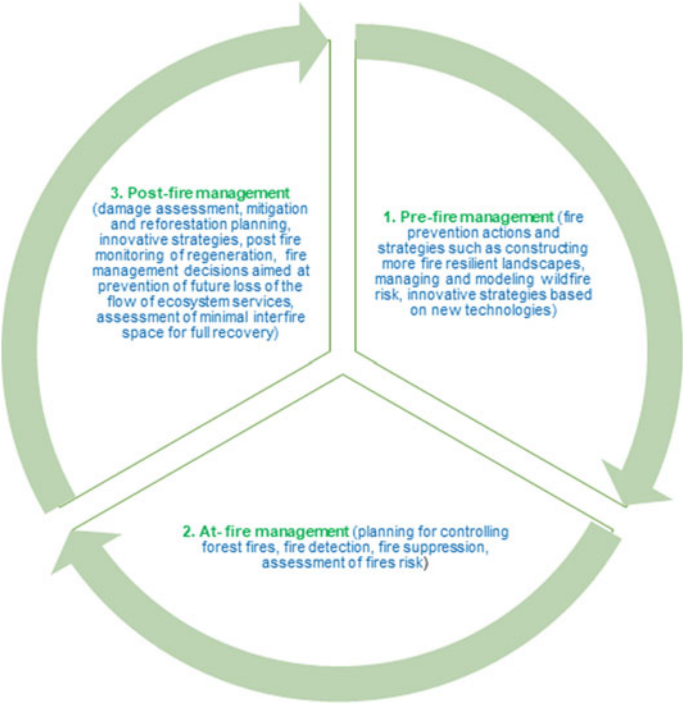

Fig. 2 A conceptual fire management framework (Daskalakou et al., 2014; Mavsar et al., 2011; Nyongesa & Vacik, 2018; Salam, 2020)

2 IoT Technologies in FFM—Forest Fire Internet of Things (FFIoT)—Socioeconomic Aspects

Wildfires are climate-related events with significant impacts on both climate change and human well-being. Technology plays a crucial role in understanding the causes of "green swan" events, providing innovative solutions to address them. Emerging technologies like the Internet of Things (IoT) and artificial intelligence (AI) have become valuable and powerful tools for responding promptly, efficiently, and innovatively to these situations (Nassef, 2022).

Remote participation in forest management can give rise to specific dynamics of power and politics, as forests are increasingly viewed as global resources (Gabrys, 2020). Figure 3 presents a visual example of Forest Fire Internet of Things (FFIoT) in a forest landscape. Various smart devices are collecting various types of data and communicating wirelessly through a gateway. The messages received by the base gateway are stored and then transferred to an online database. This collected information is readily accessible for further analysis and informed decision-making. Figure 4 provides a detailed breakdown of the four layers of FFIoT for end-users.

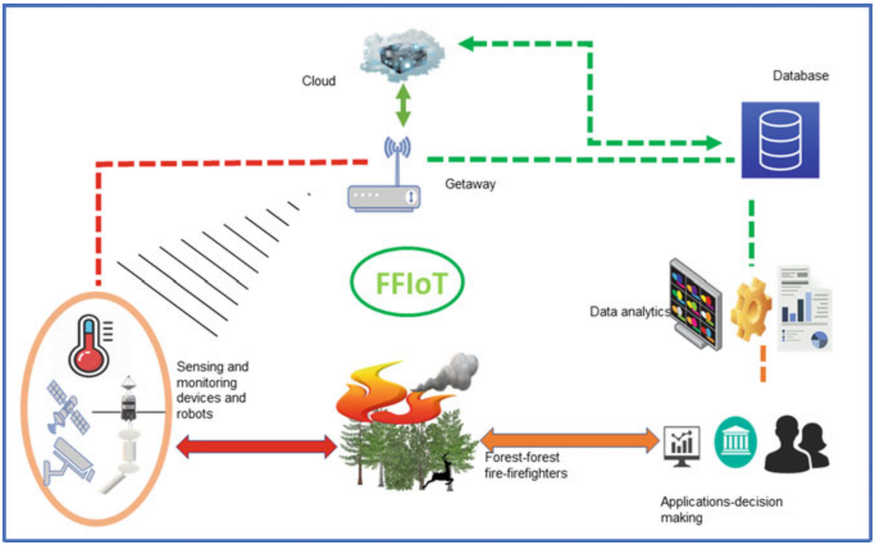

Fig. 3 A diagram of architecture of FFIoT (Icons were inserted from painting and draw.io software)

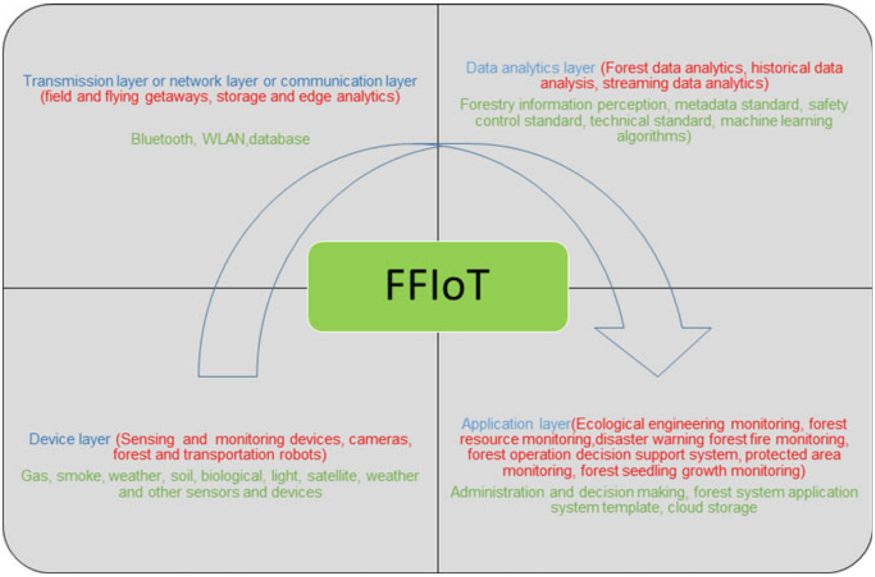

Fig. 4 A conceptual framework of FFIoT

3 Related Work—Review

We conducted this review and analysis based on the principles of forest fire management (FFM) and IoT (Internet of Things). We compiled an indicative list of Forest Fire Internet of Things (FFIoT) articles published from the beginning of 2017 through May 2022, using various databases. The search was concluded in May 2022. The keywords employed for the search included "Forest Internet of Things," "Smart Forests," "Digital Forestry," and "Forestry 4.0." We focused on studies primarily related to forest fires. While this list is not exhaustive, it provides comprehensive coverage of the topic in terms of geography and ecology, highlights key findings, addresses gaps in the literature, and outlines future challenges in the field.

Addressing the critical issue of air pollution resulting from wildfires, Mahajan et al. (2017) developed a framework utilizing IoT for predicting the concentration of particulate matter with a size of 2.5 μm or less (PM2.5), a significant air pollutant released into the atmosphere following a fire. These particles have severe adverse effects on human health, and this innovative study aims to achieve highly accurate predictions to mitigate potential health risks. The study utilized data from 119 Airbox Devices stations in Taiwan for experimentation and evaluation. Prior studies had only presented a generic model applicable to all stations. This limitation was overcome by introducing the concept of clustering monitoring stations into grids based on their distances from each other. The results have the potential to enhance air quality monitoring systems, support local and national environmental objectives, and contribute to meeting sustainable development goals (SDGs).

Dubey et al. (2018) introduced a cluster-based approach for forest fire prediction in Spain, leveraging sensor network technology. This approach involved three key steps: (a) Collecting forest fire images from sensors distributed across various geographical areas; (b) Analyzing these images using a clustering algorithm designed for forest fire prediction. This algorithm grouped clusters based on different colors and textures corresponding to specific locations; (c) Implementing a system for early forest fire detection, minimizing response time by calculating the average value of cluster trees within the sensor network.

By upgrading the existing wireless sensor network (WSN) fire detection approach, this system achieved a reduction in false alarms. The hardware components of this system included:

- A gas humidity sensor for measuring humidity and temperature.
- A gas sensor for detecting gases like carbon dioxide, carbon monoxide, methane, hydrogen, propane, etc.
- A flame sensor converting detected light into infrared light.
- A microprocessor/microcontroller, compact in size, capable of simulations, and responsible for controlling all the sensors.
- A buzzer alarm for alerting.

This application offers several advantages:

- Early detection of fires with the ability to promptly inform authorities.

- High accuracy of 96.7% on test data.
- A straightforward and simple model.

New findings from this approach include the implementation of a highly accurate fire prevention and detection system, significantly reducing false alarms. This method outperformed satellite-based forest fire detection in terms of effectiveness. Early and accurate wildfire detection plays a crucial role in limiting the fire's extent, and the user-friendly model enhances coordination efforts.

In the same year, Toledo-Castro et al. (2018) developed a forest fire controller based on a fuzzy logic model. The primary objective was to analyze environmental information, including meteorological data, oxygen levels, and polluting gases, to rapidly assess potential forest fire risks and detect ongoing fires. They also introduced decision-making methods aimed at reducing real-time analysis of environmental data. The proposed wireless sensor network (WSN) had the capability to conduct environmental monitoring, including parameters such as temperature, humidity, wind speed, rainfall, carbon dioxide and monoxide levels, and oxygen levels. This system was built upon a prototype of an IoT device distributed across various forest areas. This innovative approach to designing an effective environmental monitoring network, capable of providing scientific data essential for ecosystem management and decision-making processes, addresses one of the key challenges in environmental monitoring (Li et al., 2019). Moreover, there is potential for improvement by incorporating new sensors into the system.

Choudhry and O'Kelly (2018) highlighted that fire monitoring is among the 15 promising practices within the technological landscape of precision forestry, encouraging the participation of forestry companies. To illustrate how forest fires are perceived by society and the resulting chain reactions, they focused on the 2017 wildfire in South America, which resulted in forest owners losing at least four percent of their forests. In response to these losses, owners are now exploring ways to enhance detection and control systems using digital technologies. Regarding national parks, Peinl (2020) introduced the design and implementation of a novel, flexible, and open architectural system called ASPires, aimed at early prevention and detection of forest fires. ASPires evaluated the capabilities of a new low-power LoRa wireless technology, capable of covering long distances of up to 15 km. The system was tested for viability, accuracy, and effectiveness in three national parks: (a) Pyrin, Bulgaria; (b) Mavrovo, North Macedonia; and, (c) Pelister, North Macedonia. The system included the following components: (a) sensors for measuring temperature, air and soil humidity, carbon dioxide and monoxide levels, dust particle concentrations, wind speed and direction, and noise levels; (b) a power regeneration component or rechargeable battery; and, (c) an optional local data storage facility and wireless transmission technology. The key advantages of this system were:

- Reduction in costs and damage caused by forest fires.
- Overcoming existing drawbacks.
- Utilization of cost-effective sensors.
- Low energy consumption, whether powered by batteries or other energy sources.

- Long-range coverage and operation on free frequencies using wireless technologies.
- Deployment of flying gateways instead of field-based gateways, which are prone to damage.

These advancements represent significant progress in forest fire prevention and mitigation efforts.

In the same year, Srividhya and Sankaranarayanan (2020) recognized the need for periodic monitoring and surveillance of forest fires in vulnerable areas due to the accelerating impact of global warming on the frequency and severity of forest fires. In their work, they proposed an IoT-Fog-based framework for forest fire monitoring systems, with the goal of addressing limitations in other wireless sensor networks. The IoT-Fog framework allows for the balancing of computing and data analysis operations, distributing these functions across aggregator and central cloud layers. The cloud component plays a pivotal role in managing all fire-related notifications, issuing alerts to forest offices and individuals in the surrounding areas. Some of the main advantages of this system include low bandwidth usage, reduced latency, and the ability to handle heterogeneous data computation effectively. Future challenges in this sector include optimizing energy consumption and strategically placing Fog nodes to enhance the system's efficiency and coverage.

Post-fire forest management can benefit from the adoption of an alternative approach to reforestation, complementing the traditional method of manual planting (Gabrys, 2020). While the traditional method remains significant and widely practiced, emerging digital technologies offer the potential to plant billions of trees annually through aerial techniques involving drones and the mass planting of polycultures (mixed forests) using smart machines capable of separating various species. Additionally, planting at scale from the sky is being explored (Nassef, 2022), among other innovations. The idea that forests can transform into digital environments managed through technology to address mitigation, climate change, and environmental challenges has the potential to shift the paradigm in forest management. This vision is not distant and may become a routine practice in future forest management, accelerating the adoption of alternative reforestation methods.

A novel methodology for forest fire warning based on IoT was designed and implemented in the Jizhou forest district of China by Han (2021). This forest plays a crucial role as the primary provider of ecosystem services for the nearby major cities of Beijing and Tianjin. The system consisted of three key components: sensing, transmission, and application. The application layer of the system enabled rapid and effective communication with the fire-affected region. In general, the forest fire warning system was complex and required professional expertise and scientific input. The technical aspects involved the use of smart devices for data acquisition, transmission, control, display, monitoring, and management. This innovative system has the potential to be implemented not only in remote forest areas but also in urban and peri-urban forests, enhancing the capacity to detect and respond to forest fires effectively.

In their comprehensive review, Sahal et al. (2021) outlined the transition from Industry 4.0 to Forestry 4.0, facilitated by advanced technologies like the Internet of Things (IoT). This transition is expected to bring about social, environmental, and economic benefits, and the review provided a roadmap for this transformation. Forest fires are recognized as one of the major risks negatively impacting the environment and are a significant dimension of Forestry 4.0. Given the limited practical studies available, the review emphasizes the research gap regarding the potential adoption of the Internet of Forest Things (FIoT) for environmental sustainability. It particularly focuses on forest fire management and detection, considering it a central component of Forestry 4.0.

Singh et al. (2021) introduced a novel IoT system designed for forest fire detection and prediction in India, aiming to address previous limitations such as connectivity, edge device fire detection, and power consumption. The proposed framework improved the short-term estimation of forest fire risks and the early detection of fires through the utilization of LoRa communication and edge computing-based gateways. To detect the emergence of fires, sensor nodes with integrated sensors were deployed. These sensors measured various parameters, including temperature, humidity, light intensity, rainfall, wind speed, and infrared values. The system was powered by a battery, and local storage was available for data backup. Additionally, a computer vision node (CVN) worked in tandem with the sensor node to provide precise information.

Ntinopoulos et al. (2022) emphasized the connection between the Fire Weather Index (FWI) and climate conditions in Greece. They utilized datasets derived from daily wind speed, precipitation, relative humidity, minimum, mean, and maximum temperature, as well as solar irradiance. Regions with high FWI, indicating drier and hotter conditions, exhibited a higher likelihood of experiencing more forest fires. Meteorological information was instrumental in assessing the fire danger classification in these areas. Maintaining, expanding, and connecting databases could prove to be a valuable tool for predicting forest fires at regional, national, and global levels.

In a recent analysis, the focus was on biodiversity products that can be retrieved from space using available space assets. Among these products, those describing the abiotic drivers of ecological disturbance, including the biological effects of fire disturbance, were ranked as some of the most important products in terms of relevance, feasibility, accuracy, and maturity (Skidmore et al., 2021). The study highlights the importance of detecting the planet's dramatic changes over decades rather than relying solely on periodic (annual or seasonal) observations to align with operational and research-oriented management and reporting needs. Ensuring the continuity of free and open data, affordability, and establishing links between in-situ and remote sensing observations are essential for this purpose.

4 Conclusions and Challenges

The potential for high-value creation through improved forest fire management is one of the key environmental advantages of Forest Fire Internet of Things (FFIoT). It has the potential to enhance operational ecosystem monitoring, contributing to national and global ecological security (Li et al., 2019). The development of a monitoring system that combines remote sensing observations, in-situ measurements, and model simulations ensures high accuracy. These digital archives are crucial for monitoring planet-wide changes, including forest fires (Kays et al., 2020). Additionally, FFIoT can improve health and safety by helping to avoid dangerous locations (Hock et al., 2016). From a societal perspective, FFIoT applications shift participation from local actors to a more global stage, promoting democratic engagement and including all relevant stakeholders, thereby contributing to diverse and inclusive forest management (Gabrys, 2020; Gabrys et al., 2022). This collaborative approach fosters the development of sustainable and durable databases, and digital technologies can serve as a catalyst for environmental initiatives and regulations, transforming and expanding previous practices and technologies (Gabrys et al., 2022). Moreover, technology adoption in environmental issues can motivate the business sector to become more involved due to economic benefits.

However, there are drawbacks to adopting these new technologies from an environmental perspective. IoT can accelerate the depletion of natural resources and increase the environmental footprint due to the production of electronic devices, leading to higher waste generation and emissions (Nižetić et al., 2020). Effective recycling methods and advanced e-waste management are essential for a greener future. High energy consumption also poses financial challenges, necessitating technical advancements like energy-efficient communication and long-term batteries. Conducting life cycle assessments (LCAs) or environmental impact analyses (EIAs) is critical to evaluating the environmental footprint of these new products.

From a socio-political perspective, digital technologies can exacerbate environmental injustices and inequalities, with privileged actors having easier access. The specialization of workers in response to changing job requirements can lead to social impacts, potentially affecting mental well-being, necessitating an emphasis on the development of soft skills. Preparing the new generation for the transition into the era of big data requires an educational structure. The next steps should focus on further developing technology for data collection, statistical tools for analysis, and suitable infrastructure for data management. Creating a list of selected parameters that can be adopted universally is crucial. Starting with small-scale FFIoT projects and gradually scaling up is advisable. Collaboration across disciplines, better-established research, and a focus on avoiding socio-political inequalities and undemocratic governance are essential (Gabrys, 2020). The alignment of legal frameworks and the development of digital forest legislation are also necessary.

Lastly, in the face of significant planetary changes in which wildfires play a crucial role, the urgency for institutions to recognize the value of “born digital data” and invest in standards for informative data records that contribute to the management and conservation of natural resources is paramount.

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Socioeconomic Impacts and Regional Drivers of Fire Management: The Case of Portugal

Joana Parente, Marj Tonini, Malik Amraoui, and Mário Pareira

Abstract Wildfires are uncontrolled and unwanted fires that usually occur in forested/rural areas and burn forests, agricultural areas, and wildlands. Land abandonment, with the consequent growth of the rural–urban interface, increases the exposure and vulnerability of fire-prone regions around the World. In the last two decades, Europe experienced a high number of wildfires causing large burnt areas mainly concentrated in the Mediterranean Basin. This high fire incidence seems to be the result of human activities including land use/land cover changes, but also of climate variability and change. In the present study, we analyse the current situation in Portugal, which is the European country with the highest total number of wildfires and the second-highest total burnt area. The spatial and temporal variability of the wildfires within the country is very heterogeneous, due to the human and biophysical drivers. In this regard, four main aspects are considered and discussed: (1) the spatial and temporal distribution of wildfires in mainland Portugal; (2) the main human and biophysical fire drivers; (3) socioeconomic impacts; and (4) the main strategies for fire risk mapping and management. The main results indicate high spatial heterogeneity of the fire incidence, with higher fire activity in the northern region than the southern region, mainly promoted by a higher irregular topography and significantly different types of climate and land use/land cover characteristics. We highlight how fire incidence is strongly dependent on many biophysical and human factors/drivers and the direct and indirect socioeconomic impacts of wildfires. Methodologies and indexes developed by Portuguese authorities to map fire risk and assess fire danger

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are described. The elements discussed in this chapter result from research and lessons learned in recent years on the fire regime in Portugal and Europe. These findings can contribute to improving forest, landscape, and fire management, in Mediterranean European countries which share similar characteristics.

Keywords Wildfire · Human drivers · Spatial patterns · Fire incidence · Biophysical drivers · Burnt area · Portugal

1 Introduction

Wildfires have been an essential component of Mediterranean ecosystems since 24 million years ago (San-Miguel-Ayanz et al., 2013). This area is highly prone to fires, mainly due to the vegetation heterogeneity and the favourable climate conditions characterized by wet and mild springs and hot and dry summers, increasingly affected in recent decades by heat waves and droughts that promote the thermal and hydric stress of the vegetation (Pereira et al., 2013). Human factors may also contribute to the extent of the fire incidence in the Mediterranean basin, such as the migration of rural populations to urban areas over the last 50 years (Bowman et al., 2011). Decreasing precipitation and increasing air temperature, combined with the above-mentioned factors, increase the fire risk in the Mediterranean region, especially during the summer months (San-Miguel-Ayanz et al., 2013).

In the last two decades, wildfires have affected more than 6.2 million people and were responsible for more than 2400 fatalities, and losses with an amount of 61 billion euros around the world (Wallemacq & House, 2018). Extreme wildfire events with catastrophic consequences have become more frequent in the recent period. For example, in Portugal, wildfires of 2017 burnt 1.2 million hectares of natural land, including 25% of Natura 2000, causing 127 human fatalities and losses of about 10 billion euros (San-Miguel-Ayanz et al., 2018). Despite its smaller land area in comparison with the other European Mediterranean countries, Portugal is the European country with the highest total number of wildfires and the second-highest total burnt area (San-Miguel-Ayanz et al., 2018). The growth of the rural–urban interface has increased the likelihood of fire ignition by humans (Tonini et al., 2018). In addition, the rural abandonment contributed to the decrease in forest fuel consumption and the subsequent biomass accumulation (Pereira et al., 2014). The combination of these factors with the climate and weather conditions makes Portugal a high-fire-risk area, especially in summer (San-Miguel-Ayanz et al., 2013). The variation in fire incidence is related to landscape characteristics that can act as biological, socioeconomic, and physical drivers (Parente et al., 2018c). Regardless of the fire cause (lighting, accidental, negligent, or intentional), wildfires may have significant impacts. Wildfire's impacts and characteristics highly depend on several human and biophysical drivers, such as (1) socioeconomic parameters (Oliveira et al., 2017; Parente et al., 2018c); (2) land and forest management practices (Parente et al., 2016); (3) topography (Fernandes et al., 2016b; Parente et al., 2018c); and (4) weather and climatic conditions (Parente et al., 2018a, 2018b, 2019). In this context, identifying the regions where those fire impacts and fire drivers have more influence is of greater importance for increasing the efficiency of fire management actions.

Following this line of reasoning, the present chapter aims to briefly discuss and characterize for mainland of Portugal (hereafter, Portugal): (1) the spatial and temporal distribution of wildfires; (2) the main fire drivers, causes, and impacts; and (3) the main fire risk management characteristics.

2 Spatial and Temporal Distribution of Wildfires

Wildfires display a complex spatiotemporal pattern strongly related to forest landscape and neighbouring anthropogenic developments, such as urban and rural areas, and road and pathways networks. Fire occurrences tend to present clusters (Vega Orozco et al., 2012), where events are found closer in space and time than expected for a random distribution. Thus, cluster analyses can be applied to investigate these patterns and to disclose vulnerable areas and frame periods where wildfires are more likely to occur (Vega Orozco et al., 2012).

Portugal can be divided by the Tagus River into two regions of about the same size: (1) the northern region has a temperate type of climate with dry and warm summer (Peel et al., 2007), and is characterized by an irregular topography, flat along the western coast and mountainous towards the central and eastern side (with a pick of 1993 m), the predominance of forest and semi-natural areas, and a dense river network; (2) the southern region has dry and hot summers (Peel et al., 2007), and is characterized by lowlands dominated by agricultural areas, with the only exception of two patches of mixed and broad-leaved forest extending near the south coast at mid-altitude (with a pick of 1000 m). Not surprisingly, the northern region is much more affected by wildfires than the southern half (Parente et al., 2016; Tonini et al., 2018). Also, considering the fire dataset available by the *Instituto da Conservação da Natureza e Florestas* (ICNF, https://icnf.pt/), before the 1980s, the burnt area had never reached 10,000 ha for a single occurrence. Instead, from the 1990s to nowadays (2021, the year of the last available burnt area dataset), this threshold has been exceeded several times, especially with the catastrophic wildfire events in 2003, 2005, and 2017. Still, it must be underlined that the number of wildfires has been steadily decreasing since the early 2000s, and this tendency is followed up by its decrease with a Daily Severity Rating above five (Observatório Técnico Independente et al., 2020).

Investigating Land use/Land cover changes occurring in Portugal for two decades (1990–2012), Tonini et al. (2018) revealed an increase in the rural–urban interface more pronounced in the northwest sector and along the coast, where the transition from heterogeneous agricultural areas to urban fabric was particularly intense. This development was mainly due to urban growth and the intensification of the road network. Comparing the evolution of the rural–urban interface with the mapped burnt areas, these authors discovered that the first increased by more than two-thirds, while the latter decreased by about one-third; nevertheless, the burnt area within the rural–urban interface doubled, highlighting the importance of monitoring this interface area for adequate fire management and prevention. Even if not included in the mentioned study, the recent extreme fire season of 2017, which burnt an area of 539,920 ha of forests, shrubland, agricultural land, and artificial surfaces in one hundred and fifty municipalities in the north-central Portuguese regions (San-Miguel-Ayanz et al., 2021), is highly representative of the same undergoing process. In recent studies (Comissão Técnica Independente et al., 2018; Observatório Técnico Independente et al., 2020; San-Miguel-Ayanz et al., 2021), the list of significant factors that can potentially increase the frequency of these extreme events includes not only extreme climate conditions, but also fire causes (e.g. arsonist), fuel management, land use/land cover changes, increasing depopulation in rural areas, and increase in the rural–urban interface.

A deeper investigation of the spatiotemporal distribution of wildfires in Portugal revealed to be fundamental to detecting over-densities and trends in fire risk, allowing to address prevention and forecasting measures. Indeed, in a fire-prone country like Portugal, where thousands of events occur each year, extracting useful information from the original raw data (i.e. mapped ignition points or burnt areas and related attribute tables) is a demanding task. In this respect, statistical methods initially developed for stochastic point processes have been successfully employed in the past (Parente et al., 2016; Pereira et al., 2015). In a recent study, Tonini et al. (2017) combined different methods to detect wildfire overdensities: (1) Geographically Weighted Summary Statistics (GWSS) to explore how the average burnt area varies in space; (2) the Cross K-function to assess whether or not burnt areas of different sizes are independently distributed; and (3) the 3D-kernel density estimator (3D-KDE) to elaborate smoothed maps representing the continuous spatial density distribution of wildfires and their temporal evolution.

The results for GWSS (Fig. 1 on the right) indicate regions with (1) local mean burnt area above 500 ha localized in the central regions in Portugal (districts of Coimbra, Castelo Branco, Santarém, and Portalegre) and along the southern coast (Faro District); (2) local mean burnt area below 200 ha quite dispersed in the southern half of the country; (3) meagre and low local means predominant and concentrated in the region between Bragança and Vila Real (to the east), between Porto and Viana do Castelo (to the west) and around Lisbon (to the centre). Additionally, hot spots of the high local mean for the burnt area were identified due to a few events with a very large burnt area surrounded by several events with a small burnt area.

The cross K-function results revealed the propensity of medium wildfires (15 ha $\leq$ burnt area < 100 ha) to aggregate around small wildfires (5 ha $\leq$ burnt area < 15 ha), while large wildfires (burnt area $\geq$ 100 ha) aggregated at a larger spatiotemporal scale, indicating a return period longer and more complex than for small and medium wildfires. In more detail, the cluster behaviour of small and medium wildfires increased with the distance, with picks of cluster every 3 and 4 years, while large wildfires resulted in being randomly distributed within a distance lower than 3 km and clustered above, with two picks of cluster each 6 and 10 years.

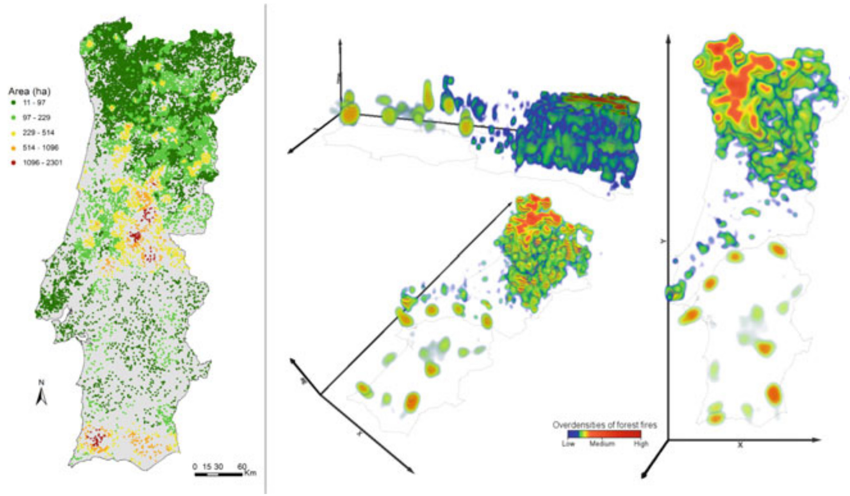

Fig. 1 3D-kernel density (on the left) and geographically weighted local means (on the right) of the burned area in Portugal for the period 1990–2013

The 3D-KDE results (Fig. 1 on the left) revealed the highest densities located in the northwestern area of Portugal, nearby the regions of Viana do Castelo, Braga, and Vila Real, and in the northern-central area, nearby the regions of Viseu, Guarda, and Castelo Branco. Lower spatial densities of wildfires were present in the southern coastal regions of Lisboa, Santarém, Leiria, and Coimbra. Paying attention to the wildfires' temporal evolution, the higher densities were registered between 1995 and 2004, while the lowest densities were disclosed in the two years, 1992 and 1993, characterized by a very low number of wildfires. The southern half of the country exhibited lower smoothed densities than the northern regions. In the central period (1998–2006), medium–high densities were spatially homogeneously distributed, with the highest values in the period 2000–2004. Finally, the volume rendering technique was employed to elaborate 3D maps representing the spatiotemporal evolution of these smoothed densities into a unique map, allowing one to visualize at glance regions and frame periods with more clusters of wildfires.

We conclude by mentioning that the wildfires' spatial and temporal distributions are two factors strongly correlated, meaning that events closer in space are also closer in time, with an increased risk for emerging megafires events.

3 Fire Drivers: Human and Biophysical Drivers

It is easier to understand the high spatial and temporal variability of the fire incidence (number of wildfires and burnt area) in Portugal by discussing the influence of the role of human and biophysical drivers on this variability. This variability presents a south-north gradient with much higher values in the North region and high differences at national and regional scales. Additionally, understanding the role of human and biophysical drivers on this variability is of fundamental importance to support forest and fire management as well as the implementation of legislation. It is worth a mention that fire characteristics (e.g. size, intensity, duration, and behaviour) and their consequences highly depend on several human and biophysical drivers, including socioeconomic factors (Nunes et al., 2016; Oliveira et al., 2017), landscape and forest management practices (Godinho et al., 2016; Parente et al., 2016), topography (Fernandes et al., 2016b), organization, shape, size, and characteristics of patches of different types of vegetation cover (Bond & Keane, 2017; Jan et al., 2018), and finally weather and climate conditions (Parente et al., 2018b, 2019; Russo et al., 2017).

At the national level, in Portugal, about 85.5% of the forest areas are privately owned (Bouillon et al., 2020). The combination of rural land abandonment within these areas and their split of land ownership creates a complex landscape mosaic of neglected shrublands and small- to large-scale forest plantations (Bouillon et al., 2020). Also, the rural–urban interface has increased by more than two-thirds between 1990 and 2012 (Tonini et al., 2018). So, the combination of such factors with the fact that most of the fire ignitions are human intentional (Parente et al., 2018c) makes it no surprise that several studies have identified as the most critical drivers of fire incidence the population density and topography/landscape characteristics (Catry et al., 2007; Nunes et al., 2016). Additionally, Fernandes et al. (2016a) have shown that wildfires larger than 500 ha were increasingly controlled by fuel-related variables, such as fuel composition, fuel connectivity, and pyrodiversity. Also, they have found that climate-weather variables only have an importance of 15% as bottom-up variables on the influence of fire size. On the other hand, extreme weather conditions (e.g. drought and heat waves), in combination with high fuel load drive extremely large wildfires (burnt area $\geq$ 2500 ha). Nevertheless, it is important to highlight the following points (Parente et al., 2018c): (1) fire occurrence (total number of wildfires) increases with population density; (2) fire incidence decreases with the distance to the nearest road; (3) fire ignition is higher at a lower altitude, and in the artificial surfaces, pastures, and heterogeneous agricultural areas; (4) total amount of burnt area increase with altitude and is higher in agricultural areas, forests (mainly *Eucalyptus globulus* and *Pinus pinaster*), and semi-natural areas; (5) slope has the lowest influence on fire occurrence but has the strongest influence in the total amount of burnt area; and, (6) fire extent is essentially driven by fire weather conditions and ignition density (Davim et al., 2022). Finally, the extent of a large wildfire is mainly a function of human and biophysical drivers that land-use planning, forest, and fuel management can partially address (Fernandes et al., 2016a).

4 Fire Causes and Fire Socioeconomic Impacts

In the last decades, EU Member States have experienced critical fire events that have resulted in the loss of human lives and significant economic and environmental losses (San-Miguel-Ayanz et al., 2021), and Portugal is no exception. Portugal has been marked by substantial landscape transformation related to land cover/land use changes and rural depopulation, especially in its interior (Medeiros et al., 2022; Poeta Fernandes, 2019). Those depopulated areas have experienced a dramatic increase in biomass amount and continuity, contributing to the rise of new fire regimes (Pausas & Fernández-Muñoz, 2012), with even more frequent catastrophic wildfires events (San-Miguel-Ayanz et al., 2018). There is no significant cause–effect relationship between the atmospheric conditions favourable for fire occurrence and fire occurrence, in the sense that ignitions in Portugal are essentially due to human activity (Amraoui et al., 2013). Additionally, human ignition is the primary cause of wildfires nowadays, accounting for about 99% of total ignitions with known causes (Parente et al., 2018c). Nevertheless, the Portuguese *Instituto da Conservação da Natureza e das Florestas* (ICNF, www.icnf.pt) categorize fire causes in a three-level hierarchical structure, and each level identifies several major categories. The first level identifies six major categories of fire cause, namely: (1) use of fire; (2) accidental; (3) structural; (4) incendiarism; (5) natural, and (6) unidentified. The second level discriminates the causes of the previous one, identifying them in groups and discriminating against specific activities. Finally, the third level divides activities into subgroups and discriminates specific behaviours and attitudes leading to a total of 70 different fire causes. For the sake of simplicity, four major categories may cluster all this information, namely: (1) negligent wildfires that comprise the use of fire and/or accidental fire; (2) intentional wildfires that include structural fire and/or incendiarism; (3) natural wildfires; and (4) unidentified wildfires. Considering the temporal distribution of such categories between 2001 and 2014, they exhibit two different trends: the number of unidentified wildfires decreases with time, and the number of negligent and intentional wildfires increases (Parente et al., 2018c).

In Portugal, most wildfires are small (burnt areas below 100 ha), as a fire extinction/exclusion policy prevails in the country (San-Miguel-Ayanz et al., 2013). However, some of these events escape to the initial fire attack and the subsequent firefighting operations, mainly of the times due to the lack of a proper number of firefighters, which might be the consequence of the tremendous amount of fire ignitions at the same time (Comissão Técnica Independente et al., 2018). Consequently, these wildfires may become large and impact a diverse range of economic, social, and environmental assets and values (Stephenson et al., 2013). Measuring these latter impacts is not easy due to the difficulty in obtaining measurable data that allow establishing scales of social, economic, or even emotional and family impacts (Viegas et al., 2017). Nonetheless, we can point to several direct socioeconomic impacts: (1) loss of human life, registering more than 110 fatalities, between civilians and firefighters, in the last 25 years in Portugal (Tedim et al., 2020); (2) short- or/and medium-term health issues due to smoke inhalation/intoxication, burns, wounds, and also mental health problems in civilians and firefighters; (3) buildings loss, such as houses and agroforestry assets (Tedim et al., 2018, 2020); (4) large expenditures on fire management, e.g. the joint budget of Greece, France, Italy, Portugal, and Spain is €2500 million each year, more focused on fire detection and suppression (Doerr & Santín, 2016).

An example of such extreme events was the unprecedented 2017 fire season, from which can be highlighted the wildfires from 17th June. Here, 64 people (between 5 and 88 years old) lost their lives, more than 200 injured people, and 458 structures were destroyed (San-Miguel-Ayanz et al., 2021; Tedim et al., 2018). Beyond the impacts described above, wildfires may also have several indirect socioeconomic impacts such as (1) reduction of tourism; (2) decrease of landscape and home values; (3) changes in soil physical and chemical properties (Jiménez-Morillo et al., 2016); (4) soil erosion (Parente et al., 2022); (5) pollution of water bodies (Basso et al., 2021; Pereira et al., 2016), which may change water quality and quantity, limit the consumption of water by humans even its disruption, and provoke the death of aquatic animals; and (6) increase of air pollution, which may contribute to premature deaths (Johnston et al., 2016).

5 Fire Risk Mapping, Modelling, and Management

Fire risk assessment on ecological, social, and economic systems is a fundamental tool for fire management and the development of cost-effective mitigation strategies. Fire risk can be evaluated using quantitative or qualitative indicators allowing the evaluation of the probability of an area being ignited by natural or artificial means in a certain period, eventually providing information on the expected positive or negative impacts in that area (Parente & Pereira, 2016). Fire risk is divided into two major components according to explanatory variables of control fire characteristics, namely: (1) a dynamic component related to variables that significantly change in time, such as weather and soil moisture conditions; (2) a structural component associated with static variables, which barely change in time, such as vegetation composition or topography.

In Portugal, the *Instituto Português do Mar e da Atmosfera* is a public institute integrated into the indirect administration of the Portuguese State that computes and publishes the Conjunctural and Meteorological Index (RCM) of rural fire danger (IPMA, 2020), which is used by firefighters and civil protection and fire management authorities. The Conjunctural and Meteorological Index is calculated daily and results from the combination of two indices: (i) the Fire Weather Index (FWI), which is updated once a day, and (ii) the rural fire hazard index, which includes a decadal structural component and an annual conjunctural component, that considers the burnt areas of the last three years, both under the responsibility of the *Instituto da Conservação da Natureza e Florestas* (ICNF, https://icnf.pt/). The integration of the two indices is performed by applying a risk weighting matrix at the pixel level of 1 km spatial resolution, and the agglutination by administrative unit (municipality and district) is carried out by weighting the highest risk values, considering the threshold of 20% of the most serious classes (IPMA, 2020).

The Fire Weather Index is the fire intensity index of the Canadian Wildland Fire Information System (Van Wagner, 1987) used worldwide at regional and global scales to assess the fire hazard (McElhinny et al., 2020; Vitolo et al., 2020). It comprises six sub-indices (three fuel moisture codes and three fire behaviour indices) calculated with observed and predicted values at 12 UTC (Coordinated Universal Time) of air temperature, relative air humidity, wind intensity, and accumulated precipitation in the last 24 h (Pereira et al., 2020). The Fire Weather Index is then classified into five classes (1-minimum to 5-maximum), and the annual conjunctural hazard is into five classes (0-zero hazard, which essentially corresponds to urban areas and water plans, to 5 maximum hazards) (IPMA, 2020).

The fire structural hazard map is based on the fact that the spatial distribution of fire incidence (namely of the burned area) is not uniform (Parente et al., 2016; Pereira et al., 2015; Tonini et al., 2017) and that the propensity of the fire depends on and can be modelled based exclusively on spatial data, namely slope, altitude, and land use and occupation (IGOT & pahl_consulting, 2020; Pereira et al., 2014). Verde and Zêzere (2010) further details this fire susceptibility modelling and fire hazard mapping that form the basis of the structural fire risk mapped for mainland Portugal by Parente and Pereira (2016). In this study, the adopted concept of fire risk includes two components: (i) the fire hazard, defined as the probability of an area being affected by a fire during a specific period, comprising the susceptibility of that area and the probability of occurrence; and (ii) the potential damage, which accounts for the vulnerability of an area to the fire and the economic value of the damage caused. In a recent study, the statistically-based approach developed by Verde and Zêzere (2010) has been compared with a stochastic approach (Leuenberger et al., 2018), opening the way for further implementation of Machine Learning based approaches for fire susceptibility mapping (Tonini et al., 2020; Trucchia et al., 2022).

Other relevant approaches to evaluate fire risk include coupling fire behaviour modelling and stand characteristics (Botequim et al., 2017) or with a social-ecological approach (Tedim et al., 2016). Like other fire hazard and fire risk assessments, the Conjunctural and Meteorological Index integrates dynamic and structural variables observed in loco or remotely using geographic information system technologies (Caetano et al., 2004; Chuvieco et al., 2010). The fire structural hazard map was developed solely based on altitude, slope, land use, and occupation. However, the explanatory and predictive value of a much broader set of population, biophysical, and socioeconomic spatial variables has been demonstrated (Oliveira & Zêzere, 2020; Oliveira et al., 2012; Parente et al., 2018c) which has already led to a reassessment of fire susceptibility and hazard for mainland Portugal (Oliveira et al., 2021).

6 Conclusion

This chapter was devoted to the characterization of socioeconomic impacts and regional drivers using the example of Portugal. To this end, we have presented and discussed: (1) the use of several simple statistical methods to characterize wildfires' spatial and temporal patterns at the national scale; (2) the main fire drivers, causes, and impacts; and (3) the main indices used and for fire risk assessment and management in the country.

We can conclude that: (1) statistical methods developed for spatial and temporal stochastic point processes allow to highlight of local fire over-densities and mapping them; (2) despite the methodology used, the distribution of wildfires is very heterogeneous in Portugal; and (3) the fire incidence patterns and the ignition dates are strongly dependent on many human and biophysical drivers strongly. Characterizing the socioeconomic impacts of wildfires remain a challenge, especially in light of the current climate changes that increase the fire risk, especially the occurrence of megafire events in fire-prone countries such as Portugal. Finally, we discussed the fire risk mapping in Portugal resulting from the combination between the fire weather danger index and the fire hazard index. The resulting maps can be used to implement and support educational activities, awareness-raising initiatives, and prevention campaigns, as well as to support planning for better allocation of monitoring systems and firefighting.

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Regional Issues of Fire Management: The Role of Extreme Weather, Climate and Vegetation Type

M. G. Pereira, J. P. Nunes, J. M. N. Silva, and T. Calheiros

Abstract It is of paramount importance to discuss and reflect on the influence that climate and land management have on fire regimes and, consequently, on the regional character of fire management. Our focus is on the Iberian Peninsula, although the results and conclusions presented here are common to many other regions of the world with a Mediterranean climate. The discussion is based on the concept of risk, starting with conjunctural risk factors, moving on to structural factors and including their interconnection. Conjunctural risk factors of weather and climate are discussed in the context of requirements for fire to occur, which include the existence of fuels, a state of dryness suitable for combustion and a source of ignition. The influence of climate and weather is discussed at different space–time scales and related to characteristics of vegetation and land management. The roles of atmospheric patterns, types of weather, extreme events, meteorological hazard indices in patterns of fire incidence, their grouping and definition of pyro-regions are presented. Within structural factors, human populations shape fire regimes by changing the ignition patterns, fighting wildfires, modifying landscapes (e.g., urbanization, deforestation and afforestation) and changing land management. Finally, the interconnection between these risk factors in the context of global changes, in particular

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climate change, and the challenges they pose to the regional landscape, forest and fire management are highlighted.

Keywords Fire management · Fire risk · Structural/conjunctural risk factors · Extreme fire weather · Climate · Land management · Vegetation type

1 Introduction

Wildfire risk mapping is a key determinant tool for fire management because is closely associated with socioeconomic impacts. Fire risk can be defined as the combination of fire hazard, which is the probability of a region being affected by a fire in a given period, which depends on the probability of occurrence and the susceptibility of the region; and potential damage, which depends on the region's vulnerability to fire and the economic value of the damage caused by the fire (Parente & Pereira, 2016).

The concept of fire risk can be divided into two components: one structural and the other conjunctural (Bergonse et al., 2021; Lourdes & Pessanha, 2009; Verde, 2010). The first has to do with essentially stationary variables or variables that vary in the long term, such as topography, land use/land cover (LULC), population or socioeconomic activities. The second depends on variables that vary in the short term, such as atmospheric conditions, in particular the occurrence of extreme events such as drought and heat waves (HW).

Weather monitoring (e.g., drought) and forecasting (e.g., HW in the short term and drought in the medium term) and, consequently, the assessment of meteorological fire danger/hazard are key components of fire management, namely for short-term fire weather risk mitigation, resource allocation and a better understanding of wildfire dynamics for active firefighting planning.

On the other hand, the type of vegetation plays a key role in the structural component of fire risk and, therefore, of fire management. For example, the wildfire risk map in Portugal includes LULC as one of the risk factors and the fire weather index (FWI) of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987), one of the most used fire hazard indices in the world, is based on the relationship between atmospheric conditions and vegetation (IPMA, 2020). The role of vegetation type is fundamental both before and after a fire, whereas (agro)forestry management activities (preventive silviculture and restoration) also play an equally fundamental role in the risk and management of fires.

All these aspects have an essentially regional character, as the spatial distribution of fires, vegetation type and atmospheric conditions are not uniform across the territory, but are characterized by great diversity and even clustering of events (Parente et al., 2016). This chapter aims to describe the role of climate, atmospheric conditions and vegetation in the danger and risk of fire and, consequently, in the management and socioeconomic impacts of fires. The focus will be on the Iberian Peninsula (IP) and Portugal in particular, as Portugal and Spain are the most affected countries in Europe both in terms of the number of wildfires (NW) and burned areas (BA). This region is a case study characteristic of the Mediterranean basin and regions of the world with a temperate/Mediterranean type of climate with dry and hot summers. The Mediterranean basin is also a hot spot for studies of climate change impacts, adaptation and vulnerability (Paeth et al., 2017; Tuel & Eltahir, 2020).

2 The Role of Climate, Weather and Extreme Events

The climate and atmospheric conditions are decisive for the occurrence of a wildfire that requires the existence of fuels, an adequate state of dryness and an ignition source (Ventura & Vasconcelos, 2006; Whitlock et al., 2010). In summary, climate determines the existence, type and life cycle of the vegetation; weather determines the state of the fuels and influences all stages of the fire; and, both, explain the spatial–temporal patterns of fire incidence (NW and BA) that are observed at global and regional scales (Pereira et al., 2019).

Climatic elements, such as surface air temperature and precipitation, determine the water availability to plants and the spatial distribution of the world's vegetation, major biomes and ecoregions (Kelly & Goulden, 2008; Woodward & Williams, 1987; Woodward & Woodward, 1987). The role of climate is also revealed by the seasonality observed in the vegetative cycle and, consequently, in the incidence of fire (Accatino & De Michele, 2013; Alvarado et al., 2017; Giglio et al., 2015; Krawchuk et al., 2009; Le Page et al., 2008; Saha et al., 2019). For example, the Mediterranean climate type is characterized by a rainy and mild period, which promotes the development of vegetation, and a hot and dry period, which promotes the thermal and hydric stress of the vegetation, when wildfire weather danger is higher (Parente et al., 2016; Pereira et al., 2005; Trigo et al., 2016a). Thus, it is not surprising the high similarity between the patterns of climate type, terrestrial ecosystems and wildfire incidence, at global and regional scales (Oliveira et al., 2018; Parente et al., 2016) as well as the identification of regions with similar fire regime—pyroregions—and climate type (Archibald et al., 2013; Galizia et al., 2021; Krawchuk et al., 2009; Pereira et al., 2022; Sousa et al., 2015a; Trigo et al., 2016a).

If climate explains the large-scale patterns of the spatial–temporal distribution of vegetation and fire incidence, the climate variability and weather types explain the characteristics of the fire regime at local and regional spatial scales, and shorter temporal scales (Dwyer et al., 2000; Rodrigues et al., 2020; Trigo et al., 2016a; Turco et al., 2018). At typical wildfire time scales (hours to days), atmospheric conditions play an admittedly important role in all fire phases (Calheiros et al., 2022; Pereira et al., 2019). Lightning causes fires worldwide, especially in the boreal regions, and large summer wildfires when associated with dry storms or with little precipitation (He et al., 2022; Pérez-Invernón et al., 2021; Sullivan, 2017). Wind, humidity and air temperature are important drivers of fire propagation and behavior (Benson et al., 2008; Pastor et al., 2003), while precipitation and air humidity help fight and extinguish fires (Awad et al., 2020).

At longer temporal scales, climate variability and weather explain other characteristics of the fire regime such as the inter-annual variability of the fire incidence and the asymmetry of the fire size distribution (Andela et al., 2019; Cansler & McKenzie, 2014; Hantson et al., 2015). For example, several studies show that about 2/3 of the interannual variability of the burned area in IP pyroregions is explained by atmospheric conditions (Pereira et al., 2005; Sousa et al., 2015a; Trigo et al., 2016a). In each region, the fire size distribution tends to be highly skewed to the right, which means the existence of a high number of small wildfires and a few numbers of extreme wildfires that tend to be responsible for the majority of the total burnt area. In the case of Portugal, 10% of the largest wildfires account for 80% of the total burnt area (Pereira et al., 2005).

A power law can be fitted to the heavy-tail wildfire size distribution and help to illustrate and explain the rarity of large fires (Kanevski & Pereira, 2017; Malamud et al., 1998; Telesca & Pereira, 2010). This distribution reveals the existence of different classes of fires, for which the fire propagation is dominated by different atmospheric/climatic conditions: drought is responsible for the propagation of large fires, the relative humidity of the medium fires, and the wind governed the propagation of smaller fires. These results are consistent with the idea that fire propagation involves limits of scale, with small-scale drivers allowing fires to propagate after ignition, but limiting further spread only when large-scale drivers exist (Slocum et al., 2010).

For regional hazard assessment and fire management support, the influence of atmospheric conditions on fires has been studied and objectively quantified in several ways, including hazard indices and meteorological fire risk (e.g., San-Miguel-Ayanz et al., 2003); fire propagation and behavior models (e.g., Pastor et al., 2003); burnt area models (Pereira et al., 2013; Sousa et al., 2015b; Trigo et al., 2016b); identification of atmospheric patterns and weather types associated with high fire incidence (Amraoui et al., 2015; Rodrigues et al., 2020); assessment of the role of extreme meteorological (e.g., HW, storms) and climatic (e.g., drought) events.

HW and droughts are the main climatic drivers of fire incidence and, in particular, extreme fires (Pereira et al., 2005). For this reason, the HW characteristics (frequency, duration, seasonality and intensity) and their influence on extreme wildfires (wildfires with BA $\geq$ 5000 ha) in mainland Portugal were evaluated for recent past and future climate conditions (Parente et al., 2018). About 130 HW were identified in 1981–2010, between May and October, but concentrated in July and August. HW characteristics show great interannual variability, clearly associated with the temporal and spatial distribution of extreme wildfires: 97% of the total number of extreme wildfires were active during an HW, 90% of the total days of extreme wildfires were also HW days; 82% of the extreme wildfires had duration contained in the duration of an HW; and 83% of extreme wildfires occurred during and in the area affected by HW. Results also show that HW should increase in number, duration and amplitude, most significantly for RCP 8.5, and the end of the twenty-first century. The results of this study should support the definition of climate change adaptation strategies for fire hazard and risk management.

Other unsuspected extreme weather events can promote extreme wildfires. On October 15, 2017, after an exceptionally hot and dry season, with unusually intense droughts and heat waves, the fire weather was extreme and fuel moisture very low when the tropical storm (former hurricane) Ophelia passed along the west coast of Portugal, promoting strong south winds over the mainland, advected hot and dry North African air, increased the rate of fire spread and growth and gave rise to several mega fire events (Augusto et al., 2020; Castellnou et al., 2018; Sánchez-Benítez et al., 2018; Turco et al., 2019).

Recently, a study characterized the drought regime in the climatic conditions of the recent past (1981–2017) using various drought indices (Standardized Precipitation Index SPI, Standardized Precipitation Evapotranspiration Index, SPEI, Reconnaissance Drought Index, RDI and Vegetation Condition Index, VCI) and evaluated the influence of drought on the occurrence of extreme wildfires (Parente et al., 2019). Results reveal that: all extreme wildfires occurred during the drought evaluated with SPI or SPEI; more than 95% of the number of extreme wildfires and 97% of the burned area occurred during the drought evaluated with one of these indices; and 85% and 87% of extreme wildfires occurred in drought-affected areas evaluated with SPI or SPEI, respectively. The relationship between drought and fire incidence is statistically significant for 3-month SPI, 3-month and 6-month SPEI, and particularly strong for moderate and severe drought. It is not clear which is the best index, but drought is decisive for the occurrence of large wildfires.

The evaluation of fire weather danger and risk is useful to support firefighters and fire management stakeholders in several activities. The Canadian Forest FWI System (Van Wagner, 1987) evaluates the severity of fire weather conditions and comprises: three indices to numerically rate the fuel moisture in three relevant forest fuel layers, including the Drought Code (DC), which assesses the effect of drought on forest fuels; and four relative indices of fire behavior, including the Fire Weather Index (FWI) and the Daily Severity Rating (DSR) (Wotton, 2009). The DSR rates the difficulty of controlling fires because it reflects more accurately the expected effort required for fire suppression (Pereira et al., 2013; Wotton, 2009). The FWI System rates the relative fire potential just based on weather data (Stocks et al., 1989), namely daily values registered at noon of four meteorological variables, namely air temperature, relative humidity, wind speed and daily accumulated precipitation. The FWI System was developed for Canada, but for a common standardized forest type and is globally and regionally computed and extensively used to rate the fire weather danger, especially in the Mediterranean basin (Bedia et al., 2012; Flannigan et al., 2016; Guenni et al., 2022; Pereira et al., 2013; Silva et al., 2019a, 2019b; Vitolo et al., 2019).

A cluster analysis carried out on the normalized burnt area revealed the existence of four pyroregions in the IP (Fig. 1), namely in the N—North, NW—Northwest, SW—Southwest and E—East (Sousa et al., 2015a; Trigo et al., 2016a). The four pyroregions differ in the intra-annual variability of the normalized burnt area, namely by the existence and dimension of peaks and month of occurrence of maximum values (Fig. 2). A recent study repeated the analysis for a longer period and, despite confirming the existence of the four pyroregions, revealed differences in the administrative regions that constitute them (Calheiros et al., 2020). The authors calculated the Number of Extreme Days (NED), defined as the days with DSR and DC above the 95th percentile, and found a relationship between the intra-annual variability of the NED and the normalized burnt area, with high and statistically significant correlation, in each pyroregion and capable of explaining the changes in pyroregions. Recent changes in the intra-annual variability of the normalized burnt area were observed in some border provinces of the pyroregions, associated with the NED and confirmed that large values of BA are strongly linked to extreme weather conditions.

This robust link was used to project the future pyroregions of the Iberian Peninsula, using simulated data from a wide ensemble of climate models for two scenarios (RCP4.5 and RCP8.5) to estimate future FWI indices (namely DSR and DC) and NED (Calheiros et al., 2021). Results revealed a significant increase of the NED, especially in the south and central Iberia, for the end of the century and the RCP8.5 scenario, mostly due to significant increases in the DC, associated with the substantial

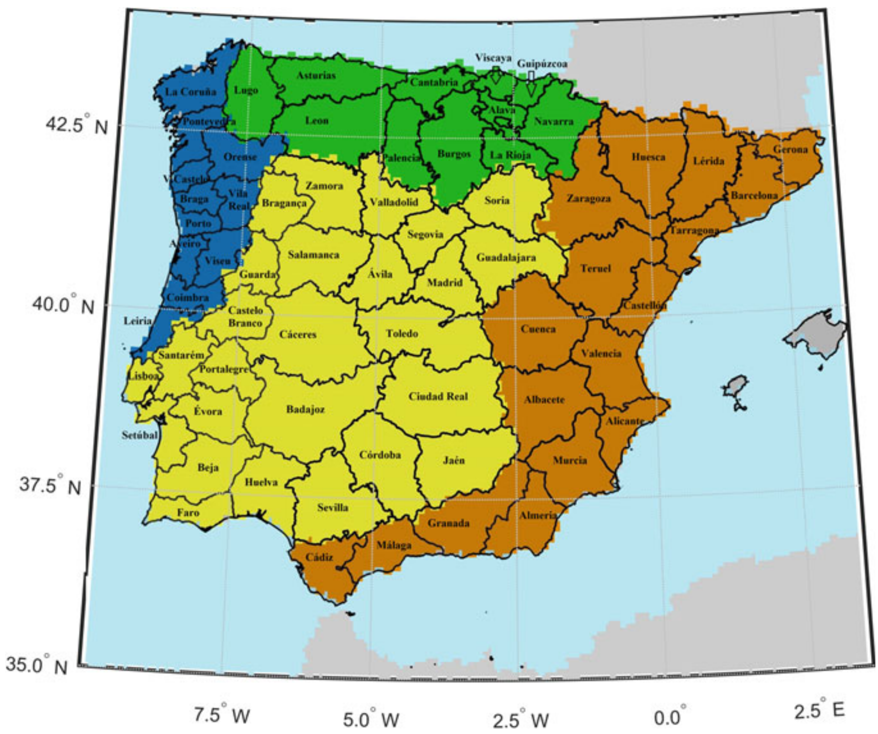
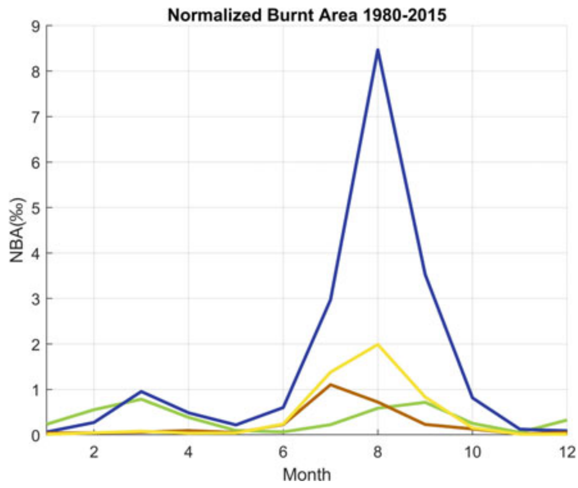


Fig. 1 The pyroregions identified in the Iberian Peninsula in the period 1980–2015 (NW in blue, N in green, SW in yellow and E in brown), the administrative regions are part of them (right panel) and the monthly averages of the normalized burnt area, computed for each month and the administrative region as the quotient between the monthly burnt area and the area of the administrative region (in per mileage) for the period (right panel)

Fig. 2 Normalized burn area from 1980 to 2015 per month



decrease in precipitation and increase in air temperature. Changes in NED intra-annual pattern should drive the pyroregions' future configuration and it is related to changes in future climate types (Beck et al., 2018). Pyroregions will move northward: The N pyroregion can be confined to the Cantabrian Mountains; the NW may include several provinces of the current N pyroregion; the SW will comprise most of the current provinces of the NW; and, E is expected to maintain its current boundaries, but changes in vegetation could lead to a new pyroregion in the extreme southeast (Calheiros et al., 2021).

3 The Role of Land Management

Besides climate, contemporary fire regimes are also impacted by human activities. Human populations modify fire regimes by suppressing natural ignitions or increasing human-caused ignitions, by increasing or decreasing the fuel loads (e.g., agriculture abandonment or prescribed fire), or by modifying the landscapes (e.g., urbanization, deforestation and afforestation). In Portugal, as in most Mediterranean countries, the land cover is largely the result of anthropogenic activities. Currently, the area of the country covered by forests is about 36% (ICNF, 2019), compared to less than 10% at the end of the XIX century (Mather & Perreira, 2006), and eucalypt and maritime pine plantations account for 48% of the forest area (ICNF, 2019). Cork and holm oak woodlands cover 34%, and the rest of the forest area comprises stone pine (6%), other oaks (3%), chestnut (1%) and other forest species (7%). An important area of the country is also covered by shrub formations and pastures (31%), and agriculture (23%).

On average, from 1996 to 2021, 41% of the annual burned area in Portugal occurred in forests, and 53% in shrublands and pastures (data from ICNF, the

Portuguese Forest Services). Analyzing the fire–vegetation relationship, namely the fire incidence by vegetation type is complex due to the firefighting activities, which modify this relationship given the decision of protecting a specific area with a specific land cover or vegetation type. Silva et al. (2019a), analyzing the long-term spatiotemporal trends of bunt area in the Iberian Peninsula, observed increasing trends of burnt area in northwestern Portugal (Braga, Porto, Aveiro districts) and decreasing trends in Galicia, Spain, with the first region showing a decrease in the area of forest and the second an increase of this area, revealing how firefighting and forest management shape the fire–vegetation relationship. The spatial pattern of the land cover types in a region may also have an impact on the fire incidence by land cover. In areas of the rural–urban interface (which is the case of northwestern Portugal), characterized by a mixture of different land cover types (urban areas, agricultural fields and forest areas), it is expected to have a different fire–vegetation relationship compared to regions largely dominated by forests or shrublands.

A fire frequency analysis in Portugal, based on burnt area maps derived from Landsat imagery for the period 1975–2005, revealed that a large portion of central and north Portugal had a fire return interval of fewer than 25 years (see Oliveira et al., 2012, for details on the imagery used and on the frequency analysis). In the regions covered predominantly by forests, there were not many fires but they were large, whereas in regions dominated by shrublands, the fire regime was characterized by more frequent but smaller fires (Oliveira et al., 2012). The size of wildfires is a very important factor in the fire–vegetation relationship, with large fires being less selective in terms of land cover (Barros & Pereira, 2014; Nunes et al., 2005). Nunes et al. (2005), using 506 fires that occurred in Portugal, investigated if fires select given land cover types for burning by comparing the proportions of land cover types present in burned areas and their respective surroundings. Results showed that fires are selective, with small fires exhibiting stronger land cover preferences than large fires, and that there is a marked preference for shrublands followed by forests, while agriculture is avoided. Following a different methodological approach, Barros and Pereira (2014) obtained similar results. The ranking of land cover types according to fire proneness, from less to most fire-prone was as follows: annual crops, evergreen oak woodlands, eucalypt plantations, pine stands and shrublands. All land cover types exhibited reductions in fire preference as fire size increased. Other studies obtained similar rankings (Moreira et al., 2001, 2009; Silva et al., 2009). The lower selectivity of eucalypts compared to pine may be explained in part by their economic value and active management, and suppression effectiveness, which contributes to mitigating the effect of severe weather conditions (Barros & Pereira, 2014).

Population and land cover determine much of the complex fire patterns in Portugal (Costa et al., 2011; Nunes et al., 2016). Nunes et al. (2016) analyzed the drivers of forest fires in Portugal at the municipal level. Concerning land cover, they found that uncultivated land was a factor that contributed to an increase in the burnt area. Uncultivated land, resulting from agricultural abandonment, more than doubled in the last five decades, and it is covered largely by vegetation that is very prone to fire. An analysis of the land cover changes in Portugal in the last 100 years concluded that from 1907 to 1990, the area covered by forests and woodlands increased, a process called forest transition (Mather & Perreira, 2006) and that after 1990, there was a substantial conversion of forest areas to shrublands (Oliveira et al., 2017).

(Calheiros et al., 2022) assessed the relationships between vegetation/land use, fire weather and burnt area at high resolution (municipalities) for Portugal with recent data (2001–2019). ERA5-Land reanalysis dataset was used to compute the FWI indices, and the percentiles of the DSR (DSRp) were assessed with the large wildfires (BA > 100 ha). In detail, each wildfire was associated with the highest DSR recorded during the wildfire duration in the municipality or municipalities. This analysis revealed that the days with DSR above the DSRp between 85 and 95 were responsible for more than 80% of the total BA in mainland Portugal. Nevertheless, this threshold presents significant spatial diversity at the municipal scale. A cluster analysis revealed the clusters with different thresholds that explains 80% or 90% of BA. Further investigation showed that distinct vegetation and/or land use justifies this spatial variability. Indeed, it was demonstrated that the clusters located in coastal regions are predominantly covered with forest and have a large BA with the most extreme meteorological conditions, or very high DSR percentiles. On the contrary, clusters placed in the eastern parts of the country have the largest amount of shrublands, and the BA occurred more frequently with less extreme meteorological conditions or lower DSR percentiles. These results should be used in firefighting and regional fire management (Calheiros et al., 2022).

Sá et al. (2018) modeled fire incidence with vegetation, precipitation and anthropogenic drivers, finding that urban and agricultural areas control fire absence, while forests and especially shrublands area are the main drivers of fire incidence. They also found the need to discriminate between irrigated and rainfed agriculture when studying fire–agriculture relationships. Eucalypt plantations are often viewed as highly flammable due to the nature and structure of the fuel complex, but the burnt area of this species did not increase over time (1980–2017) even with an increase in the area of eucalypt (Fernandes et al., 2019). This study also found that large-scale conversion of maritime pine to eucalypt stands implied lower fuel accumulation. Fernandes and Guedes (2011) analyzed each type of forest in Portugal the fire risk, how species respond to fire, and identified preventive silvicultural treatments. For eucalypts, fire danger (defined as the ease of ignition and fire propagation and its difficulty of extinction) is reduced in 39% of situations and it is extreme in 42% of cases. Tall eucalyptus (especially if open) is less vulnerable to fire; low and closed formations occupy the opposite extreme. Selection by fire is proportional to its availability in the landscape. For pines, fire danger is high and extreme in 60% and 23% of cases, respectively. The low maritime pine forest is very vulnerable to fire. Maritime pine tends to burn in a higher proportion than its availability in the landscape, especially in large fires, and its probability of burning is maximum.

Population density and distribution can also influence the fire regime through its contribution to ignitions. In the work by Calheiros et al. (2020) described earlier, an analysis of fire occurrence, burnt area and weather conditions (FWI) for the IP between 1980 and 2015 revealed clustering into four pyroregions with distinct fire regimes. One interesting result of this analysis is how different frequencies of ignitions influence these regimes. The Northwestern Iberia pyroregion has a large number of ignitions, and hence, a large number of small fires which can evolve into large fires when weather conditions are extreme. Therefore, the climate is a determinant of the occurrence of large fires. In other pyroregions in the Southwestern and Eastern parts of the Peninsula, extreme weather conditions are more common but ignitions are less frequent, thus making climate relatively less important. Ignitions have been related to population density by Catry et al. (2009), and the northwestern part of Iberia has a relatively higher population density due to more dispersed settlement patterns than elsewhere in the peninsula.

Land management also affects the socioeconomic impacts of fires. The most obvious impact is through the exposure of population and property to fire impacts, potentially resulting in damage or fatalities (San-Miguel-Ayanz et al., 2020); areas with larger population densities and/or longer rural/urban interfaces are more exposed to impacts. But there are less obvious secondary impacts, of which the potential impacts on water resources are an example.

Water supplies are often collected from fire-prone watersheds (Robinne et al., 2021) since agricultural watersheds present higher rates of water contamination. But fires can have significant impacts on water quality, as discussed by Nunes et al. (2018) and Robinne et al. (2021). The ash created by fires can be mobilized to the stream networks, leading to excessive turbidity and increasing the concentration of nutrients, heavy metals or organic compounds; these problems can overwhelm the capacity of existing water treatment systems, and there are many cases of water supply limitations as a consequence of fires, often for several years afterward. In this case, the exposure problem might be reversed, as areas with lower population density might be more affected since they are preferential sources of water supply, and since water supply systems for smaller communities tend to have smaller water treatment capacities and therefore be less resilient to disruptions.

4 Conclusions

This chapter showed how climate combines with land management patterns to affect the regional impacts of fires, therefore presenting unique challenges to regional fire and forest managers. Climate drives the occurrence of fires by promoting the growth of vegetation, and thereby the creation of fuel; and a dry period which promotes fire occurrence and spread. The spatial distribution of population and vegetation is important in determining sources of ignition, ease of fire spread (especially for less intense fires), and difficulty of fire suppression. They also determine the potential socioeconomic impacts on populations and natural resources. In Mediterranean landscapes, and particularly in Portugal, vegetation distribution is mostly derived from human decisions, and therefore, land management plays a crucial role in fire risk.

While not much can be done about climate and extreme weather patterns, land management can be used to mitigate fire risk. This can include special attention to the distribution of forest and agriculture areas, promoting land-use patterns which limit fire spread; or differentiated prevention measures according to the distribution of population and natural resources (e.g., water supplies). Since these factors have a strong spatial variability, the best level of planning to address them is the regional level, where best practices and solutions can be adapted to existing and projected conditions.

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