Introduction: FIRElinks, a Community for Society and Science

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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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