Intelligence Versus Inferno: How Artificial Intelligence Can Be Used to Monitor and Manage Wildfires in Europe

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Abstract

Escalating wildfire occurrences in Europe, particularly in the southern Mediterranean region, are presenting significant challenges to socioeconomic, environmental, and ecosystem services. The increasing frequency and severity of these wildfires are straining resources and emphasizing the need for a better understanding of the relationship between suppression capacity and fire behavior in wildfire management. The following research addresses the urgent need for more proactive, knowledge-based, and technologically driven fire management strategies, throughout all four stages of wildfire response – fuel and land management, fire preparedness, fire suppression, and post-fire management. Artificial Intelligence (AI) is becoming increasingly significant in climate change adaptation, especially regarding wildfire science and management. The integration of AI techniques, such as machine learning, showcases a promising avenue for enhancing preparedness, detection, and response to wildfires, highlighting the broader potential of advanced technology in addressing environmental challenges. While AI holds promising potential for enhancing preparedness, detection, and response to wildfires, it is still in the early stages of development and presents obstacles and limitations to full implementation. Despite demonstrated successes in wildfire preparedness and suppression, such as through the World Economic Forum’s FireAId initiative, further research is essential to minimize potential negative consequences associated with this evolving technology.

Keywords

Artificial Intelligence (AI): refers to computer systems that can perform tasks that typically require human intelligence to execute. These tasks include learning, reasoning, problem-solving, understanding natural language, speech recognition, and visual perception (Joiner, 2018). AI systems can be designed to operate autonomously or assist human decision-making, and they often involve the use of algorithms, machine learning, and data analysis to improve their performance over time (Soori et al., 2023).

Land Management Strategies (LMS): encompass a diverse set of practices addressing sustainable land use. These strategies include sustainable planning, biodiversity conservation, soil management, forest practices, water resource conservation, fire management, urban planning, agricultural sustainability, conservation easements, and community engagement (Neidermeier et al., 2023). LMS aims to balance economic development with environmental preservation, ensuring the health of ecosystems and promoting long-term resilience (Kirchherr, 2023). It involves collaboration between government agencies, communities, and environmental organizations to achieve effective results in land use. The strategies focus on optimizing land use efficiency, minimizing environmental impact, and engaging local communities in decision-making processes (Alibašić, 2022).

Machine Learning (ML): a subset of AI that focuses on the development of algorithms and statistical models enabling computer systems to perform tasks without explicit programming (El Bouchefry & de Souza, 2020). It involves the use of data to train models, allowing machines to learn patterns, make predictions, and improve performance over time. ML encompasses various
techniques, such as supervised learning, unsupervised learning, and reinforcement learning, and finds applications in diverse fields, from image recognition and natural language processing to recommendation systems and autonomous vehicles (Tucci, 2023).

**Wildfire Management:** refers to the planning, coordination, and implementation of strategies to prevent, control, and mitigate the impact of wildfires. This approach includes various stages such as fuel and landscape management, preparedness, suppression, and post-fire management (Fernandes et al., 2016; Moore, 2019). Strategies involve reshaping landscapes to reduce fuel loads, implementing measures for early detection and surveillance, actively combating fires, and addressing the aftermath to minimize the risk of subsequent natural disasters (Fernandes et al., 2016; Moore, 2019). The goal is to protect lives, property, ecosystems, and valuable resources while considering factors like climate conditions, land cover, and human interactions with the environment (Beighley et al., 2018). Innovative technologies, including AI and ML, are slowly integrating into wildfire management to enhance efficiency and preparedness.

1. **Introduction**

Wildfires in Europe, particularly in the southern Mediterranean countries and across the Iberian Peninsula, are escalating in frequency and severity due to climate change, land abandonment, and shifts in landscape and fuel management (Neidermeier et al., 2023). This surge creates substantial socioeconomic, environmental, and ecosystem service challenges for the continent (Forest Fires in Europe, 2021). The summer of 2023 alone witnessed over 515,000 hectares burned, which created significant ecological and economic repercussions (Gill, 2023). As these extreme events intensify, the strain on firefighting resources increases, with potential long-term impacts on health and safety conditions.

Changes in the fire regime, supported by scientific evidence indicating alterations in fire regime patterns in various parts of the world, challenge the resilience of ecosystems and socio-ecological communities (Pausas & Fernández-Muñoz, 2012; Fernandes et al., 2014). Reports of extreme fire behavior are on the rise, further emphasizing the need for proactive fire management strategies (Collins et al., 2013; Montiel-Molina and Galiana-Martín, 2016; Metlen et al., 2021; Thompson et al., 2022). Recognizing the urgency, EU leaders are calling for increased investments into firefighting resources and strategies in the most affected and at-risk regions (Gill, 2023), despite the evident limitations in the suppression capacity imposed by the fire behavior (Fernandes et al., 2016), and the evidence that such a strategy has already proven to be a mistake, having led many fire-prone regions to the firefighting trap (Collins et al., 2013; Ingalsbee, 2017; Castellnou et al., 2019).

Effective, integrated, and sustainable fire management involves four main stages according to Moore (2019) and Fernandes et al. (2016): fuel and landscape management, fire preparedness, fire suppression, and post-fire management. Strategies for minimizing risk encompass reshaping fuel and land management, adopting preventive measures, and coordinating efficient responses to wildfires (Ackermann et al., 2023). The interplay between diverse land cover and land use...
practices requires targeted strategies, considering factors like species composition, climate conditions, and existing land management practices (Palaiologou et al., 2020). This approach aims to mitigate the growing threat of wildfires across Mediterranean ecosystems.

The emergence of artificial intelligence (AI) presents a transformative force in addressing climate-related challenges, particularly regarding wildfire management. Computers and AI, despite their relatively short existence, are evolving rapidly and changing our understanding of the world (Roser, 2022). As investments surge, the potential applications of AI in climate-related data analysis become increasingly apparent. Already integral in transitioning from a carbon-based economy, AI’s ability to process vast datasets rapidly is crucial for climate-related insights (Xu, 2021). In fire science, recent EU initiatives like SAFERS and TREEADS demonstrate a commitment to harnessing AI for early detection, decision-making, and preparedness (McGowan, 2023; European Commission, 2021). However, challenges such as human intervention needs, energy consumption, and ethical considerations must be addressed to ensure the responsible and sustainable integration of AI in climate change mitigation strategies (Duffy, 2023; Ekin, 2019; Jain et al., 2023).

The following research aims to address the escalating threat of extreme wildfires in Europe, particularly in the southern Mediterranean countries and the Iberian Peninsula, by way of technological and AI solutions. Delving into the socioeconomic, environmental, and ecosystem services challenges posed by the growing threat of wildfires, this research strives to provide insights into the urgent need for more proactive and technologically driven fire management strategies. By acknowledging the evolving role of computers and AI and their rapid impact on human understanding of the world, the research aims to explore the applications of AI in climate-related data analysis for sustainable integration and implementation in climate change mitigation strategies.

2. Wildfire Management in Europe

2.1 Impact of Wildfires in Europe

Extreme wildfires are becoming more frequent in Europe, especially in the southern Mediterranean countries (e.g., Sarris et al., 2014; Ruffault et al., 2018; Rodrigues et al., 2023). While wildfires are a natural component of specific ecosystems, they are growing and intensifying in various areas, primarily due to climate change, land abandonment, and alterations in fuel management (e.g., Parente et al., 2018, 2019; Ruffault et al., 2018). These changes yield significant socioeconomic, environmental, and ecosystem services implications for Europe (Neidermeier et al., 2023), and they also adversely affect air and water quality, biodiversity, soil health, the aesthetic appeal of landscapes, and the rural economy (e.g., Forest Fires in Europe, 2021; Magro et al., 2021; Fernandes et al., 2022; Bruni et al., 2023). Wildfire risk doesn’t solely stem from hazard or exposure; instead, it emerges at the intersection of hazard, exposure, and vulnerability. Hence, addressing vulnerability is crucial in consistently managing the complexities of fire—before, during, and following the event (Ackermann et al., 2023;).
The summer season of 2023 alone saw over 515,000 hectares of land burned by wildfires (Gill, 2023) in Europe, 41% of which falls within the *Natura 2000*[^1] protected land area (Joint Research Center, 2023). All seven of the largest wildfires across the continent this year were in Greece and Spain, following long-term drought and higher-than-normal air temperature (Joint Research Center, 2023). This is spreading resources thin and costing the government significant amounts of money to respond to and manage such devastating disasters. The EU deployed more than 10 firefighting aircraft, 500 firefighters, and 100 vehicles to help suppress the wildfires in Greece this year. They also called on the neighboring countries of Cyprus and Tunisia for support with fire suppression efforts (McGovan, 2023). The fires resulted in an estimated aggregate cost of over €1.66 billion in damages for the country (Harmsworth, 2023).

In response to the 2023 summer fire season, EU leaders recognized the urgent need for increased investment in additional personnel and equipment in the southern Mediterranean countries that were most severely impacted. According to firefighting unions, the escalating workload resulting from extensive summer wildfires is significantly straining staff, jeopardizing their health, dampening morale, and potentially undermining their ability to effectively respond to forest fires, floods, and other disasters in the future (Gill, 2023).

As the frequency and severity of extreme weather conditions such as wildfires worsen, so too do the conditions of those who are employed to combat them. In fact, some European countries are starting to see a downturn in the number of firefighters due to increased concerns over the health and safety conditions of being exposed to fires (Folk & Broniatowski, 2023). Moreover, the share of overall expenditure allocated to fire services by the government has remained constant since records were first initiated in 2001, according to a Reuters research report released in September 2023 (Gill, 2023). This is spreading resources even thinner, rather than setting countries up for success in fighting wildfires.

Especially in areas that rely on volunteer firefighting services, there is dwindling incentive to support the initiative, as is the case in Portugal. Jan Willem Goudriaan, general secretary of the European Public Sector Union, said “recruiting more volunteers would not be enough without additional hiring of highly skilled professionals. Many rural services have been depleted of their capacity to act. Thinking that volunteer firefighters alone will be able to solve this challenge is a mistake” (Gill, 2023). The EU is calling for more investments in the necessary equipment and training to prepare firefighters for the growing risks of working in the industry, including illness and accidents. However, the narrative appears to predominantly emphasize the response capacity of fire suppression, lacking a perspective that recognizes the interdependence between suppression capacity and fire behavior (e.g., Palheiro et al., 2006). This omission overlooks the influence of the dynamic interaction among fire-weather conditions, fuel load, and connectivity, factors that collectively determine the size of each fire (OpenAI, 2023).

[^1]: *Natura 2000* Network: A European ecological network of protected areas established to ensure the conservation of biodiversity and the sustainable use of natural resources. It comprises Special Areas of Conservation (SAC) and Special Protection Areas (SPA) designated under the Birds Directive and the Habitats Directive, respectively. The network aims to safeguard a wide variety of habitats and species across European Union member states, promoting the maintenance and restoration of ecological balance (*Natura 2000 Protected Areas Network*, 2023).
2.2 Integrated and Sustainable Fire Management

Fire management spans a wide spectrum of applications, categorized into four distinct groups. First, there's fuel and landscape management, focusing on determining the necessity and timing for reducing fuel load or available vegetation susceptible to burning. Next is preparedness, strategically employing surveillance to prevent ignitions on days with hazardous fire weather, that might cause harm to individuals and assets. Fire suppression involves actively combating fires, efficiently managing resources, and predicting fire behavior to identify strategic opportunities for successful firefighting operations. Once the fire is extinguished, it is important to conduct a post-operation assessment to identify potential rekindling areas. Lastly, post-fire management involves emergency stabilization efforts and minimizing the likelihood of subsequent natural disasters (Fernandes et al., 2016; Moore, 2019).

2.2.1 Fuel and Landscape Management

The first step in minimizing the risk and impact of wildfires involves rethinking fuel and land management strategies. A healthy, low-flammability landscape is crucial for reducing ignition and flame spread, especially as catastrophic wildfire seasons intensify globally, calling for a reshaping of these approaches.

Strategies and techniques should be promoted for integrating the use of managed fires, management options for restricting the potential spread of fire, and long-term options that include an increase in the rotation and change of tree species (Casartelli et al., 2023). Encouraging practices such as prescribed fires, vegetation removal, and chemical treatments to manage fuels and slow wildfire spread, along with the implementation of better procedures and regulations, is essential (Casartelli et al., 2023). Embracing Nature-Based Solutions like grazing, fire-smart forestry practices, and crop mosaics, while promoting methods that break fuel continuity vertically and horizontally, will also contribute to effective wildfire management (e.g., Fernandes, 2013; Ascoli et al., 2023; Casartelli et al., 2023; Lecina-Diaz et al., 2023; Pais et al., 2023; Pulido et al., 2023).

Successful fuel and land management strategies include the utilization of fuel breaks and prescribed burns. Fuel breaks are clear zones strategically placed to halt or redirect the spread of wildfires by depriving them of fuel. They can be created artificially by clearing vegetation or by utilizing naturally existing features like roads or rivers (Agee et al., 1999). Prescribed burns are intentional fires set under controlled conditions by land managers to reduce flammable vegetation and mitigate wildfire risks. Pairing fuel breaks with broader treatments like prescribed burns can significantly diminish the magnitude, severity, and impact of wildfires in natural areas (Pacheco et al., 2021).

Greece faced a devastating wildfire season in 2023 and has begun exploring innovative new techniques. A recent study scrutinized landscapes' susceptibility to wildfires, analyzing regional species, climate, and management methods. Tailored fuel management plans were devised for 25 communities, aligned with vegetation density, and computational simulations evaluated the efficacy of different strategies to reveal the significant influence of diverse land cover and land use practices on fire propagation (Palaiologou et al., 2020). A targeted fuel management initiative
emerged, varying depending on the needs of each region, pivotal in reducing both the area affected by fires and their intensity (Palaiologou et al., 2020).

In the broader context of Mediterranean climates, analysis should focus on the most vulnerable landscapes, considering vegetation makeup and species flammability. Research on the impacts of fire in each region is crucial due to varying vulnerability (OpenAI, 2023). Similar to Greece's approach, utilizing technology and wildfire simulation programs to predict fire spread proves helpful.

Given the complex interaction observed in the Greek study within Mediterranean ecosystems, an effective approach involves the aforementioned fuel and land management strategies. Developing ecosystem-specific fuel management plans tailored to vegetation density in various communities is instrumental. This entails strategies suited to each region's characteristics, considering factors like species composition, climate conditions, and existing land management practices. Computational simulations, as conducted in the study, would enable the evaluation and identification of optimal strategies for different landscapes. Emphasizing forest-centered fuel management programs, proven effective in reducing fire extent and intensity, could significantly contribute to mitigating wildfire risks across Mediterranean ecosystems.

2.2.2 Fire Preparedness

Every area requires different prevention strategies for wildfires based on their climate, land conditions, and human interface with the environment (Beighley et al., 2018). Therefore, wildfire risk prevention should be addressed in specific sectoral legislation (Casartelli et al., 2023). Fire preparedness involves teaching communities about fire risks, establishing evacuation plans, and raising awareness of safety measures. It includes proactive steps like managing vegetation to reduce flammable materials, early detection through surveillance tools, and continuous monitoring systems. Planning for emergency responses, practicing firefighting strategies, and coordinating efforts among agencies, communities, and firefighting teams are all critical components to ensure a swift and effective response to wildfires.

Part of preparedness includes adequate education and awareness of wildfires, how they manifest in certain areas, and what individuals must do to minimize their risk. Enhancing education and access to information is crucial for increasing public awareness. This involves teaching communities about the intricacies of wildfires and cultivating a population well-versed in fire preparedness to respond effectively to these natural disasters (Beighley et al., 2018).

Another aspect of preparedness includes the systematic monitoring of fire weather conditions, with a focus on spatiotemporal variability. Understanding these conditions forms the foundation for identifying long-term trends, aiding in the strategic planning of fire prevention, suppression, and overall management strategies (Carta et al., 2023). The assessment of fire risk plays a key role as well, employing various studies that leverage climate model simulations under different scenarios. These assessments provide insights into expected changes in fire dynamics, potential large-scale wildfires, and the subsequent impacts on both intensity and occurrence (Wang et al., 2020). The implementation of a Fire Danger Rating System (FDRS) emerges as a potential
strategy as well, serving the dual purpose of alerting the population to emerging fire risks and assisting operational agencies and firefighting personnel in their planning endeavors (Kotroni et al., 2023). Additionally, advancements in decision support systems, as exemplified by the U.S. and Canada, leverage sophisticated algorithms and geographic information systems. These systems furnish critical tools, including weather information, fire behavior predictions, and economic assessment tools (Kalabokidis et al., 2016). Lastly, the text emphasizes the necessity of transnational collaboration, exemplified by initiatives like the DISARM project. This collaborative effort, spanning countries such as Greece, Bulgaria, and Cyprus, aims to establish a unified strategic framework to effectively address the intensifying threat of wildfires exacerbated by climate change (Kotroni et al., 2020).

2.2.3 Fire Suppression

Fire suppression is the least researched and developed category, which is evident in the difficulties Mediterranean countries face in effectively extinguishing wildfires once they ignite. Fire suppression can be addressed through responsive and technical methods, with the choice of strategy depending on the typical scale and impact of wildfires in different regions.

An example of a common strategy employed for wildfire suppression is the use of air tankers, which are aircraft specifically designed for aerial firefighting and are equipped to drop fire retardants or water onto wildfires. A computer simulation model called AIRPRO, which evaluates the productivity and effectiveness of air tankers in wildfire suppression, helps to increase the effectiveness of this strategy (Simard, 1979). Comprising five components—administration, environment, fire, ground suppression, and air tanker utilization—the model utilizes 300 equations to test various combinations of air tanker resources and tactics to minimize suppression cost and fire damage (Simard, 1979). However, evaluating the overall cost-effectiveness of air tankers is challenging due to limited data and uncertainty about their effectiveness in aerial firefighting (Calkin, 2014).

The increasing technological advancements in unmanned aerial vehicles (UAVs) have created innovative possibilities for combating wildfires as well. A new forest firefighting system utilizes swarms of UAVs capable of continuously dispensing extinguishing liquid onto the fire front, emulating the effect of rain (Ausonio et al., 2021). The UAVs can seamlessly replace their own batteries and refill extinguishing liquid when needed, allowing them to be more self-sufficient and require less human involvement (Ausonio et al., 2021). The proposed system demonstrates potential effectiveness in combating low-intensity and limited-extent fires or supporting existing

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2 DISARM Project: funded by the European Union and the participating countries within the Interreg Balkan-Mediterranean initiative, aimed to establish a common strategic framework for addressing the challenges posed by wildfires. The project brought together Greece, Bulgaria, and Cyprus, countries that have faced significant wildfire challenges in recent years. The primary goal was to develop, validate, and operationally apply a set of services utilizing state-of-the-art observational and modeling techniques. The DISARM project focused on creating an innovative, integrated observation and early warning system to assist authorities in preventing, addressing, and mitigating the adverse impacts of wildland fires, particularly considering their intensification due to climate change (Kotroni et al., 2020).
forest firefighting techniques (Akhloufi et al., 2021). The use of UAVs in wildfire management has gained traction globally, with laws such as the John D. Dingell, Jr. Conservation, Management, and Recreation Act in the United States encouraging their expanded deployment (Ausonio et al., 2021). UAVs offer rapid response, flexibility, and access to hard-to-reach locations, aiding in fire prevention, detection, and monitoring. This technology represents an area of fire suppression that warrants further development and testing.

2.2.4 Post-Fire Management

In post-fire management, one of the most challenging discussions revolves around deciding whether it's more beneficial to intervene and facilitate the recovery of burned land or to leave it undisturbed to heal naturally. Previously, post-wildfire management has focused on extracting salvage logs and burned trees to reduce fuel sources and minimize the potential for future ignitions (Yildiz et al., 2023). While aimed at reclaiming the forest's natural and economic value, this practice involves disturbing burned areas, potentially leading to adverse effects such as disruptions in the carbon cycle, increased soil erosion, and impacts on vegetation cover (Yildiz et al., 2023).

A study conducted following the 2017 Sapadere fire in Antalya, Turkey looked at the evolution of vegetation cover in relation to post-fire road construction and the resultant debris left behind. Researchers compared satellite imagery from 2017 (pre-fire), 2019, and 2021 (post-fire) to analyze vegetation recovery in the burned area. They observed areas utilizing different post-fire recovery techniques to determine which strategies were most successful.

A significant change in land use noticed in the study was the construction of fire roads throughout the burned area. This is a commonly employed strategy post-wildfire for removing salvage logs and cleaning up debris. It can be a beneficial strategy for minimizing the impact of future fires, as it creates fuel breaks and supports the containment of fires in the future (Agee et al., 1999). However, the study found that areas subjected to post-fire management practices displayed a slower vegetation recovery rate when compared to undisturbed areas (Yildiz et al., 2023).

2.3 The First Signs of a Paradigm Shift in Fire Management in Europe

The fire policy in the European Union has been focusing more closely on strategies to suppress wildfires, rather than prevent them. However, more recently the European Commission has stated that “if Europe is to slow down the effects of climate change, it is imperative to move away from a limited reactive approach of fire suppression to a planned approach of fire prevention” (European Research Executive Agency, 2022). The pervasion of severe wildfire incidents has highlighted the constraints of fire suppression strategies, so EU countries must transition towards more effective prevention measures to adapt to the evolving wildfire landscape (European Research Executive Agency, 2022). The European Green Deal, which was signed into legislation in May 2023, includes the European Commission’s new forest strategy. The new plan focuses on strategic monitoring of forests, data collection and reporting, advancing research and innovation agendas in
forestry knowledge, and establishing an inclusive EU forest governance framework (European Research Executive Agency, 2022).

Studies are already being conducted on different land management strategies (LMS) across Europe (Neidermeier et al., 2023). Different regions require different strategies depending on factors such as climate and land makeup, emphasizing the multi-faceted approaches that must be taken to address this issue (Marques et al., 2016). Specifically, researchers have found that Mechanical Fuel Removal (Beighley et al., 2018) is the most suitable strategy for most of the continent, while herbivory (Neidermeier et al., 2023) would also be beneficial in central Europe, and prescribed burns (Pacheco et al., 2021) would work best in the southern regions (Fernandes et al., 2013; Neidermeier et al., 2023). Further, they discovered clear potential in employing multiple LMS simultaneously to tackle fire risk, as more than 27% of high-risk areas proved suitable for two or more LMS (Neidermeier et al., 2023).

The European Union has also dedicated efforts towards better fire preparedness strategies, launching programs designed specifically to tackle these gaps. The FirEUrisk project, launched in 2021, promotes comprehensive wildfire management strategies that emphasize risk assessment and reduction across all stages of wildfire control (Steering Committee of FirEUrisk, 2023). The goal of this project is to tackle the anticipated future conditions in the EU resulting from climate and socio-economic shifts (Steering Committee of FirEUrisk, 2023). Members of FirEUrisk are vigilantly monitoring the wildfire situation in each country, offering support to authorities, educating the public about the root causes, fostering discussions on building resilient landscapes and addressing post-fire recovery. Additionally, they are closely studying the major fires occurring in 2022 to gain insights into fire behavior, community and authority response, and containment efforts. The collective efforts of the FirEUrisk consortium aim to enhance fire management across Europe, offering guidelines for better training, fire preparedness, and heightened public awareness to mitigate the impact of wildfires on vulnerable communities, economies, and ecosystems in the region.

Recently, the region of Catalonia in Spain has turned to the Ecosystem Management Decision Support (EMDS) System to standardize the process of allocating Management Areas for Fire Suppression Support (MASS), which are areas that alter fire behavior, diminishing the wildfire's intensity, and markedly enhancing the effectiveness and capacity for fire suppression. (Gonzalez-Olabarria et al., 2019). Factors considered while designating MASSs encompass the increased chance of nearby large fires, the potential for fire spread, proximity to valuable at-risk resources, accessibility for machinery, availability of adequate water sources, and opportunities for fuel management (OpenAI, 2023). The integration of accessibility, water supply, and fuel management when designating these areas sets the essential criteria for enabling effective fire suppression actions while simultaneously enhancing safety levels (Gonzalez-Olabarria et al., 2019). This study aids Catalonia's firefighting service in its fire suppression efforts by employing a blend of strategic and tactical approaches. The strategic solution pinpoints critical locations across the landscape for fire suppression activities, while the tactical solutions identify essential management actions within these specific locations (Gonzalez-Olabarria et al., 2019). This
example represents the overlap between the different stages of fire management; the research done in Catalonia highlights the importance of fuel management and land control strategies as a suppression tactic for fires in the region.

On the policy front, it is equally important to craft legislation that reflects the needs of a given region and climate. Within the context of Portugal, there was an extensive overhaul of policies and legislation concerning forest fire defense after the wildfire seasons of 2003 and 2005 (Mateus and Fernandes, 2014; Pinho and Mateus, 2019). This reform centered on five key areas: bolstering territorial wildfire resilience, decreasing wildfire occurrences, improving firefighting and wildfire management efficiency, rehabilitating ecosystems, and adapting to a more functional organizational framework (Resolution of the Council of Ministers no. 65, 2006). However, the devastating fire season of 2017 triggered a shift from an emphasis on robust fire suppression policies to prioritizing prevention. Portugal introduced a National Plan for Integrated Fire Management, outlining three primary priority areas for fire prevention: fostering a sustainable rural landscape, safeguarding rural areas, and ensuring the safety of individuals and properties (Council of Ministers, 2018). Initially, the emphasis is on safeguarding people and property, progressively integrating further preventive measures using regulatory, informative, and collaborative policy tools. Over the medium to long term, the aim is to cultivate a sustainable rural landscape, primarily employing economic and territorial policy instruments outlined in the Landscape Transformation Program (Council of Ministers, 2020).

Technology has started to be introduced as well. The FirEUrisk project conducted various wildfire trials on designated pilot sites to enhance Europe's capacity for wildfire containment (Daunt, 2023). This initiative has mapped every square kilometer of Europe, considering its climate, landscape, and socio-economic activities, intending to heighten awareness among civilians and governing bodies regarding wildfire risks (Daunt, 2023). An additional study conducted in 2021 by Portuguese researchers aimed to explore how satellites can help keep an eye on harmful gases like carbon monoxide (CO) and methane (CH4) during big wildfires in Portugal through analysis of satellite data (Magro et al., 2021). The satellite provided detailed pictures of how these gases spread in the air during and after the fires. The researchers found big plumes of CO during the wildfires, and the satellite could track how the gases moved, which is crucial for understanding wildfires better and figuring out how to manage them (Magro et al., 2021). This study shows how using satellites can help keep a close watch on these harmful gases during wildfires and improve strategies for dealing with forest fires in the future.

2.4 Challenges of Implementing a Sustainable Fire Management Strategy in Portugal

Similarly to many other Mediterranean countries, Portugal faces significant wildfire risk due to several factors: a substantial portion of forest lands being left unmanaged; escalating fuel loads in quantity and distribution; a high frequency of undesired fire ignitions, especially during severe burning conditions; and the compounding impact of climate change, leading to prolonged and intensified hot and dry weather patterns, thereby extending and heightening critical periods for extreme fires (Beighley et al., 2018; summarized by OpenAI, 2023).
Many residents living in rural communities are beginning to move into the cities, creating plots of abandoned land area and causing alterations in land use. More agricultural and forested areas are left unattended and lacking maintenance than ever before (Beighley et al., 2018). This negligence aligns with fragmented land ownership patterns that discourage forest management and fire planning investment. Despite increased investment in firefighting resources, Portugal continues to experience heightened fire activity, as evidenced by the trend in annual burned areas over the last four decades (Beighley et al., 2018). Lindon Pronto, a senior expert at the European Forest Institute and a former firefighter, states, “We can't keep just throwing money at the problem” (Daunt, 2023). The EU needs to start by building awareness from the grassroots level and actively working to make the landscape less susceptible to fires. Educating individuals and establishing comprehensive value chains across the landscape are essential (Daunt, 2023).

The problem of extreme fires is fundamentally economic. Balancing the management of landscapes that yield low economic returns, considering current societal demand levels, yet exhibit high productivity of fine fuels (those conducive to fire spread), poses a significant challenge for landscape managers in southern Europe (OpenAI, 2023). In many of these territories, the fire regime will tend to worsen if efficient payment mechanisms for ecosystem or landscape services are not implemented, if the role of fire and herbivory in these forest and pasture landscapes is not recognized, and even if it is not assumed that most pedological conditions do not allow agricultural and forestry exploitation above profitability thresholds capable of keeping rural communities active (Moritz et al., 2018).

3. Materials and Methods

This research intends to synthesize the knowledge on how Artificial Intelligence can be positively used for wildfire prevention in Europe, while also exploring the risks, limitations, and downsides of implementing these technological-based solutions. The research organization process and culminating deliverable will include the background and research gathered from the literature review, insight from a current pilot project being conducted with similar goals and values, and a SWOT analysis of the technology use. This will allow for a better understanding of both the positive and negative consequences of including AI-based technologies in decision-making to speed up the development of better and more well-suited climate- and fire-smart strategies (language synthesis support from OpenAI, 2023).

3.1 Literature Review

The following study begins with a comprehensive literature review focused on the wildfire landscape in Europe, identifying the multifaceted aspects crucial for understanding and mitigating these disasters effectively. This review encompasses an extensive exploration of the diverse approaches necessary to address the complexities of wildfire occurrences in the European context. Subsequently, the study progresses to examine the contemporary methodologies employed in managing wildfires, providing an in-depth analysis of the current strategies and their effectiveness.
The research extends to include the evolution, use cases, and diverse applications of AI within the realm of climate-related challenges, specifically regarding wildfire management. This segment critically evaluates the historical trajectory of AI applications, explores its multifaceted uses, and scrutinizes the diverse arenas where AI has been effectively employed in addressing challenges posed by wildfires and broader climate-related issues. Moreover, the study delves into the limitations and constraints that AI encounters when utilized in the context of climate challenges, shedding light on crucial areas that require further exploration, research, and development (language synthesis support from OpenAI, 2023).

The resources cited in this literature review were derived from extensive studies conducted on wildfire management. Insights into AI technology were curated from researchers and scientists actively engaged in studying and assessing the benefits, impacts, and limitations of this field. The selection of papers was carried out through Google Scholar using the following keywords, always accompanied by the expressions "fire management" or "wildfire management": "artificial intelligence", "machine learning", "neural networks", "evolutionary algorithms", "reinforcement learning", "knowledge modeling", "symbolic reasoning", and "model logics". Priority was given to scientific articles, published in peer-reviewed journals, but reports (grey literature) were also used in a complementary way.

3.2 Strengths, Weaknesses, Opportunities, and Threats Analysis

In the process of evaluating the effectiveness of AI in wildfire management, a SWOT analysis was conducted. This analysis aimed to identify the strengths, weaknesses, opportunities, and threats associated with the utilization of AI in this context. To achieve this, a combination of insights garnered from the literature review and the specific successes and challenges highlighted in the case study were analyzed and compared. The literature review provided a broad understanding of the prevailing trends, techniques, and potential capabilities of AI in wildfire management, while the case study offered nuanced, real-world examples of the actual successes and challenges encountered when employing AI within this domain. This combination of theoretical knowledge and practical observations formed the foundation for a comprehensive SWOT analysis, allowing for a thorough examination of the potential and limitations of utilizing AI for this purpose (language synthesis support from OpenAI, 2023).

4. Results and Discussion

4.1 Emergence of Artificial Intelligence in Fire Management

Despite their short existence in our society, computers and AI have fundamentally altered our perception, knowledge, and habits. The continuation of this history holds monumental significance for the future of both our world and our own lives (Roser, 2022). Technology underwent rapid evolution within a very short period, integrating into our daily routines so quickly that it is easy to overlook the relatively recent emergence of this industry. Our society is amid a technological revolution, and this technology has become the focus of ongoing research aimed at
increasing our understanding of its potential applications and limitations (Dwivedi et al., 2023). Investments in AI technology have seen a rapid surge; the doubling time for training computation has been reduced to a mere six months (Roser, 2022). Many computer scientists, economists, and investors predict that we are on the edge of significant advancements in artificial intelligence and machine learning (Chandna, 2022). As this technology continues to grow more powerful, we should anticipate its impact becoming even greater (Roser, 2022).

One of the most encouraging benefits of artificial intelligence is the ability to use it for examining and analyzing massive data sets about the climate. As our technological and data systems grow more complex, scientists are obtaining massive amounts of information that is tedious to compile and analyze by hand (Xu, 2021). AI can do this much faster, while also observing patterns and comparing data to different models. Today, most AI applications focus on instructing computers to analyze patterns in images and data, enabling them to identify new instances in diverse environments (OpenAI, 2023). Showing a computer hundreds of images of, say, red traffic lights or potatoes, allows computer scientists to create applications that recognize these things and, where necessary, act on them” (Chandna, 2022).

This technology is already being used to efficiently connect data sets from satellites and observations with model predictions, to detect trends and forecast future events (Mastrola, 2023). “These machines will help sort through, summarize, and prioritize the huge quantities of information we interact with every day” (Chandna, 2022). Currently, AI is being used to feed many processes within the chain of activities related to transitioning from a carbon-based economy to a net carbon-zero economy. This ranges from designing energy systems using lighter materials, transitioning to a smart energy grid, and implementing sustainable agricultural practices, among other things (Ahmad, 2022). These are all beneficial measures to assist in our shift to a more sustainable society, and a lot of attention has been spent on integrating AI with creating more sustainable human-made systems. However, it is time to start looking at how AI can also be applied to ecosystem protection and disaster prevention efforts.

Some companies are starting to promote this transition. In the past five years, Google has been combining advanced AI technology with satellite imagery to map large wildfires in real time (Matias, 2023). This technology has successfully alerted millions of people to fires in their area and has also been used to help predict where a fire will spread, leveraging machine learning to model fire dynamics, help with firefighter training, plan effective fuel treatments, and battle large-scale fires more safely (Matias, 2023). Other smaller-scale startups, such as Robotto in Denmark, Dryad Networks in Germany, and Kerlink in France, are all beginning to look at how to connect ground-based sensing technologies, satellite connectivity and monitoring, and terrain and heat maps to predict, identify, and respond to wildfires (EuroNews with AP, 2023; Flaherty, 2023). Similar projects have already launched and seen success in other parts of the world, such as in the United States (Chan, 2023). Investment in the research and development of these technologies is crucial for the management of our global climate crisis, especially in protecting critical ecological areas and ecosystems from fire (OpenAI, 2023).
During the first half of 2019, the European Union saw a threefold increase in the number of forest fires compared to the past decade (Forest Fires in Europe, 2021). In 2018, vulnerable ecosystems within the Natura 2000 network, which are home to numerous endangered plant and animal species, saw approximately 50,000 hectares devastated by fires, accounting for roughly one-third of the total burnt area (Forest Fires in Europe, 2021). The increasing threat of wildfires is closely linked to global warming; due to rising temperatures and more prolonged periods of drought, it is anticipated that the annual number of days featuring high to extreme wildfire danger will escalate across Europe (San-Miguel-Ayanz, 2020). Mitigation alone will not be enough to lessen possible impacts of climate change, which is why it is important to start utilizing developing technology to prevent these impacts from causing damage in the first place wherever possible.

4.2 Current Uses of Artificial Intelligence for Wildfire Management

Artificial intelligence has emerged as a valuable asset for climate change adaptation, with capabilities ranging from identifying vulnerable regions to modeling future climate scenarios and assessing risks and opportunities for businesses and infrastructure (OpenAI, 2023). Through the processing of extensive datasets from climate models, satellite imagery, and various sources, AI provides crucial insights for decision-making and preparedness in the face of climate change (Jain et al., 2023). Its application in wildfire science dates back to the 1990s, starting with neural networks and expert systems and later evolving to incorporate machine learning (ML) techniques within environmental sciences (Jain et al., 2020). Recognizing the potential, the European Union has recently increased its consideration of AI technology, launching initiatives to research, design, and test wildfire recognition systems (McGovan, 2023). While these efforts are still being developed, the overall focus of AI research has predominantly been on the modeling and mapping aspect of wildfire management.

Figure 1: Chart representing frequencies of AI-related papers for each phase of the fire management system, to quantify how much development is being done in AI technology for each step for each section and highlight the unbalanced distribution of research at each stage
In 2020, the EU launched the Structured Approaches for Forest Fire Emergencies in Resilient Societies (SAFERS) program funded by the Horizon 2020 project. SAFERS is working to bolster the resilience of communities across Europe throughout the various stages of the forest fire emergency management cycle (SAFERS in Brief, 2020). The initiative involves the development of an integrated platform, incorporating a Forest Fire Decision Support System, and leverages information from diverse sources and projects, such as earth observations and satellite data from Copernicus and GEOSS, fire sensors embedded in forests, topographic data, weather forecasts, and even crowdsourced data from social media and other applications (SAFERS in Brief, 2020). This collective information aims to equip both citizens and first responders with real-time, on-the-ground situational insights about wildfires in their region. Artificial Intelligence algorithms process gathered data to produce valuable insights for improved preparedness planning. This includes the creation of risk maps, early identification of active fires, predictions on fire propagation, delineation of burned areas and fire fronts, estimations for impact assessments, and maps outlining habitat recovery (SAFERS in Brief, 2020). Additionally, the SAFERS Decision Support System makes recommendations based on the emergency phase (prevention and preparedness, detection and response, restoration, and adaptation), as well as the current situation, drawing from a semantic knowledge base (SAFERS, 2020). The goal is to expand upon the demonstrations conducted in France, Greece, Italy, and Spain and establish a comprehensive wildfire-control system to implement across Europe (McGovan, 2023).

Another EU-funded project, TREEADS, is taking a much more ambitious approach aiming to cover all three stages of wildfires – before, during, and after a burn (McGovan, 2023). The emphasis will be on at-risk forests for wildfire development, with the goal of creating new products for fire response and incorporating them into a comprehensive Fire Management platform by optimizing and reusing existing socio-technological resources (McGovan, 2023). The project

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3 Horizon 2020: The European Union's flagship funding program for research and innovation, running from 2014 to 2020. It aimed to drive economic growth and create jobs by investing in breakthrough innovations. The program funded a wide range of projects across various scientific and technological domains, fostering collaboration among researchers, industry, and other stakeholders. It encompassed areas such as health, environment, energy, information technology, and more. Horizon 2020 has been succeeded by the Horizon Europe program, which spans from 2021 to 2027, continuing the EU's commitment to supporting research and innovation initiatives (OpenAI, 2023).

4 Copernicus: A European initiative developed by the European Union in collaboration with the European Space Agency (ESA) and the European Environment Agency (EEA). It utilizes a series of Sentinel satellites to observe and collect data on Earth's atmosphere, land, oceans, and climate. This monitoring program offers freely accessible data that contributes to applications such as climate change assessment, disaster management, and urban planning. The Sentinel satellites provide timely and accurate information, supporting decision-making processes in various sectors, including agriculture, forestry, and emergency response. Overall, Copernicus plays a vital role in enhancing our understanding of the Earth's dynamics and facilitating sustainable management practices (OpenAI, 2023).

5 GEOSS (Global Earth Observation System of Systems): A global initiative that aims to build a comprehensive and coordinated system for observing the Earth. It brings together various Earth observation resources, such as satellite data, ground-based measurements, and modeling systems, into a unified framework. GEOSS is designed to provide open access to environmental data and information, fostering international collaboration for addressing global challenges related to climate change, natural disasters, and sustainable development. Coordinated by the Group on Earth Observations (GEO), the GEOSS initiative facilitates the sharing of data and knowledge among governments, organizations, and the scientific community to support informed decision-making and advance our understanding of the Earth's complex systems (OpenAI, 2023).
introduces a real-time risk assessment tool capable of receiving multiple classification inputs, alongside an innovative neural network-powered risk factor indicator (McGovan, 2023). TREEADS will utilize alkali-activated construction materials that integrate post-wildfire wood ashes, contributing to the establishment of a model for fire-adapted communities – a very sustainable and ecologically friendly approach (McGovan, 2023). Advanced AI techniques and diverse toolsets are employed in their strategy for prevention and preparedness (European Commission, 2021). One strategy involves the utilization of drones and high-altitude balloons to detect fires early, data collection for firefighting crews, and potential assistance through the deployment of fire-suppressant materials (Ausonio et al., 2021). A comprehensive four-layer approach is employed: low-altitude drones for pinpointing fire hotspots, mid-altitude drones for dispensing fire suppressants, high-altitude balloons for a broader perspective, and satellites for an overall view (Ausonio et al., 2021). The project is also experimenting with virtual reality headsets to train firefighters who are not typically tasked with handling wildfires, which includes instructing city firefighters to manage blazes in diverse terrains should the need arise (Ausonio et al., 2021).

In total, more than 26 technologies for fire protection and suppression will be enhanced, developed, and validated as part of the TREEADS cooperation (McGovan, 2023).

Forecasting fire spread and burned area is important for minimizing the broad and immediate impact of wildfires. Prior research has endeavored to address this void primarily using mathematical models, but predictive methods would empower decision-makers to manage extensive data more efficiently and swiftly (OpenAI, 2023). A research group at the University of Coimbra is experimenting with the use of Genetic Programming to predict potential burned areas from forest fires (Pereira et al., 2022). This step employs technology for data modeling and anticipating the impacts of fire burns (Pereira et al., 2022). Researchers found that using this type of modeling can give a more accurate prediction of land burned, which will help to better understand fire patterns and minimize potential future threats.

4.2.1 The World Economic Forum FireAId Initiative

All data in the following section was sourced from Altiok et al. (2023) unless otherwise cited.

In 2022, The World Economic Forum launched the FireAId initiative aiming to unlock the capabilities of artificial intelligence and machine learning tools for forecasting and combating wildfires. Following the launch of this project, Koç Holding successfully piloted a wildfire risk mapping and logistical planning initiative in the South Aegean and West Mediterranean regions of Turkey. This undertaking enhanced wildfire prediction through the integration of static and meteorological datasets, leading to reduced response times and minimized risks for firefighters. The subsequent case study analysis includes an exploration of the project's objectives, methodologies, and outcomes, highlighting its successes and challenges in implementing AI-driven wildfire risk management strategies. The study thoroughly addresses preventive, containment, and response strategies, illustrating how the initiative integrates static and meteorological datasets for enhanced wildfire prediction, reducing response times and minimizing risks for firefighters. An evaluation of the short-term and long-term goals of the FireAId project
offers insight into the different stages of the process, demonstrating the potential to revolutionize wildfire response through a semi-autonomous AI-controlled fire defense system.

The FireAId project identified areas where the desired impact could be achieved through various wildfire risk-management strategies. Preventive measures rely on cooperation from municipalities and individuals, such as enforcing local laws and raising public awareness, and these efforts may be limited by the inability to patrol all at-risk areas. To enhance prevention, the project incorporates inputs from sensors, satellite and drone footage, and crowdsourced intelligence, transforming raw data into actionable information for rangers. Planned containment measures focus on limiting the damage caused by wildfires, which requires careful planning by firefighters and forestry professionals. However, changing environmental conditions add complexity and require comprehensive planning tools. The last strategy, response, involves swift and well-designed actions to stop a wildfire already in progress. Despite challenges, previous experience and tried approaches often prove most effective, emphasizing the importance of timely implementation over perfection. The FireAId project aims to combine these strategies to achieve a holistic and impactful wildfire risk management system.

In the short term, the FireAId project is dedicated to creating a prediction engine that incorporates trends observed through data and analysis of previous fires. The goal is to identify concerning patterns within fire-affected environments and test various intervention measures. This endeavor unfolds through stages, beginning with a clear definition of the problem and solution requirements, aligning targets with firefighting strategies—prevent, contain, and respond. The subsequent stage involves data consolidation, connecting diverse inputs, from ground sensors to orbiting satellites, to construct a comprehensive data landscape reminiscent of the brain's reliance on multiple senses. Following this, attention turns to turning the accumulated data into actionable information, emphasizing predictions related to wildfire outbreaks, propagation trajectory, and intervention measure effectiveness. The final stage introduces simulation capabilities, allowing the forecasting engine not only to predict outcomes but also to observe the impacts of interventions in comparison to baseline scenarios. Long term, the FireAId project aspires to revolutionize wildfire response by minimizing delays through a semi-autonomous AI-controlled fire defense system. This system, integrated with forecasting and actuation planning, envisions a future where simulated outcomes inform preventative or responsive measures. However, the realization of such autonomous systems relies on incremental advancements in refining predictive data.

The World Economic Forum's Artificial Intelligence and Machine Learning platform is spearheading the FireAId initiative, aiming to harness AI and machine learning innovations for wildfire prediction and prevention. Launched in January 2022, the initiative collaborates with technology companies, government, civil society, and international organizations to address the $50 billion global cost of wildfires annually. Koç Holding initiated the first FireAId pilot in Turkey, producing an AI-driven wildfire risk map, while Deloitte has contributed significantly to the Forum's AI for wildfire prediction and prevention efforts since joining in June 2022. The initiative seeks to fast-track the development of responsible AI solutions through a multi-stakeholder approach and partnership-building. The core of the solution concept for wildfire
prediction revolves around utilizing satellite imagery and weather data. Contrary to the misconception that wildfires are solely a "weather problem," this approach considers the crucial influences of geography and human activity. Fine differentiations in terrain and combustible vegetation types, along with real-time and static geographical data, contribute to more accurate predictions. The forecasting tool aims not only to predict wildfire outbreaks but also their trajectories and speed of propagation, ultimately guiding the best response. The proposed digital twin, a collaboration between Deloitte and NVIDIA, creates a simulation environment that combines AI with the physics of fire, allowing firefighters to test intervention measures and optimize resource management for crew safety. Recognizing the urgent need for an advanced analytical model to enhance fire suppression planning, the FireAld project aims to provide Turkish Ministry of Agriculture and Forestry with a decision support tool for optimal resource allocation during wildfires. The project, conducted in two phases, involved generating a wildfire risk map based on dynamic and static datasets and creating an optimal resource allocation model after ignition, with a focus on the South Aegean and West Mediterranean regions of Turkey. The initiative addresses the limitations of existing tools by considering both meteorological and static parameters, offering a comprehensive approach to estimating wildfire risks.

However, this endeavor was not without hurdles. The FireAld project faced several challenges in data acquisition and utilization. Accessing data from two ministries, the Turkish Ministry of Agriculture and Forestry and the Turkish Ministry of Environment and Climate Change, led to delays and necessitated new agreements between government bodies. Maintaining a constant data flow and avoiding compatibility issues required a collaborative effort with stakeholders and data providers. Setting standards for future data collection proved challenging due to the lack of up-to-date or high-resolution data in some cases. Unpredictable human behavior, responsible for 80% of fires in Turkey, added complexity to risk prediction, with the need for better methods to measure human activity in at-risk areas. Additionally, an imbalanced dataset, where no-fire instances greatly outnumber fire instances, posed a bottleneck for algorithm accuracy. The sheer scale of data, with sectioned-out areas as small as a few kilometers and a massive amount of historical data, required careful consideration of under-sampling and cross-validation scenarios, along with parallelization for feature engineering and model training.

Data barriers pose significant challenges in the field of wildfire management. Accessing accurate and timely data is crucial for predicting and preventing wildfires, but freely available data often lacks quality or frequency. Satellite imagery, a key data source, has limitations such as low resolution and infrequent updates. The challenge extends to integrating various data sources, ensuring data accuracy, and addressing the sparsity of fire events in datasets. The lack of global standards for data collection and format further complicates the situation, emphasizing the need for a collaborative, international effort to establish guidelines. Machine learning barriers also hinder wildfire prediction efforts. Building predictive models for wildfires requires addressing non-linear relationships, model complexity, and generalization across diverse geographical regions. Randomness in wildfire ignition and difficulties in transferring knowledge between locally trained models are notable challenges. Additionally, computational resource limitations,
including the need for high-performance hardware, pose obstacles to developing and deploying sophisticated ML models. Technical expertise, organizational collaboration, and awareness barriers further underscore the complexity of addressing the multifaceted challenges in wildfire management. A holistic, interdisciplinary approach involving stakeholders, governments, and organizations is essential to overcome these barriers and effectively combat wildfires on a global scale.

The study concludes with a call to action that underscores the necessity for governments, the private sector, academia, and international organizations to join forces, utilizing their strengths to craft impactful solutions in response to the escalating wildfire challenges. It emphasizes the potential for irreversible damage to occur to natural ecosystems and human lives if this issue is overlooked. Governments hold significant influence and should support experts and developers in finding a balanced approach to ecological preservation, security, and fiscal responsibility. The study advocates for a paradigm shift from reactive approaches to a proactive and preventative stance. In addition, the need for transparent communication is underscored, along with drawing insights from successful open-source practices. International partnerships with institutions and voluntary participation in pilot programs are also key, with a strong emphasis on gathering diverse technical expertise from a wide variety of institutions and individuals.

Wildfire risk management is a complex challenge that goes beyond firefighting. It involves controlled burns, lots of pattern and data analysis, and intricate prediction systems. The hurdles involved range from data availability to the demanding computational resources needed. Therefore, utilizing data, artificial intelligence, high-performance computing, and the cloud is crucial for the effective management of wildfire risk. The devastating impact of these fires on livelihoods and natural resources emphasizes the urgent need for the research and development of more advanced solutions. Governments have the authority to empower agencies and create incentives for academia and industry to actively engage, which experts argue should become a higher priority. Additionally, international collaboration efforts spearheaded by organizations like the World Economic Forum can address the outlined global issues and more, setting standards and creating better pathways for various entities to access data. Corporate involvement, open collaboration, and a focus on global attention are essential to tackle the wildfire problem. Access to advanced tools and resources tends to be more prevalent in developed countries, so it is important to broaden efforts and extend support to developing nations, to ensure equitable access to these essential resources. Initiatives like the Deloitte and Koç Digital projects are model examples, offering immediate value and exhibiting the potential for significant progress to be made in combating climate risks posed by wildfires around the world.
4.3 Potential Future Implementations of Artificial Intelligence for Wildfire Management

AI systems have the potential to decouple economic growth from rising carbon emissions and environmental degradation (Malliaraki, 2021). AI as a stack of data, learning algorithms, and sensing devices can help with both impact and resource decoupling (OpenAI, 2023). Varying degrees of data science programs have been used in recent years to analyze, map, and predict fire behavior. Piyush Jain - a research scientist with the Northern Forestry Center of Canada – et al. (2020) have been reviewing machine learning applications for wildfire management. According to McGill University researcher Issam El Naqa, “machine learning is an evolving branch of computational algorithms that are designed to emulate human intelligence by learning from the surrounding environment” (El Naqa, 2015). Furthermore, it “can improve automatically through experience” (El Naqa, 2015). By the end of 2019, Jain and colleague’s research encompassed 300 pertinent publications, revealing the prevalent employment of machine learning methods like random forests, MaxEnt, artificial neural networks, decision trees, support vector machines, and genetic algorithms across various problem domains (Jain et al., 2020). This highlights the potential for integrating contemporary machine learning techniques—such as deep learning and agent-based learning—within wildfire sciences, particularly when dealing with extensive multivariate datasets.

The SWOT analysis below serves as a platform for envisioning potential applications for the future. It presents an opportunity to identify and explore other innovative uses of AI in tackling challenges linked to climate change, ranging from extreme weather events to ecological conservation and resource management.
### Strengths

1. **Data Analysis:** AI excels at processing large amounts of climate data quickly, enabling efficient analysis and pattern recognition.
2. **Real-time Monitoring:** AI and satellite technology allow for real-time monitoring of wildfires, aiding in early detection and response.
3. **Risk Prediction:** AI algorithms can provide high-fidelity predictions, helping manage and mitigate wildfire risks effectively.
4. **Decision Support:** Systems like SAFERS use AI to offer decision support, enhancing preparedness and aiding in on-the-ground situational awareness.

### Weaknesses

1. **Human Intervention:** AI can make errors, necessitating human verification and intervention.
2. **Energy Consumption:** AI systems demand significant energy, contributing to environmental concerns and requiring sustainable approaches.
3. **Biased Data:** Ethical issues arise from biased data, potentially leading to skewed outcomes, and hampering the effectiveness of AI applications.
4. **Complex Algorithms:** The complexity of AI algorithms poses challenges in identifying biases or errors, impacting the reliability of this technology.
5. **Accessibility:** Ensuring affordable and accessible AI technology for all nations, especially low-income ones, is a critical concern to address.

### Opportunities

1. **Ecosystem Protection:** AI presents an opportunity to extend its applications beyond carbon-focused initiatives to ecosystem protection and disaster prevention.
2. **Global Collaboration:** Initiatives like SAFERS and TREEADS demonstrate the potential for global collaboration in developing AI-powered fire management systems.
3. **Ethical Frameworks:** Addressing ethical concerns through transparency, inclusivity, and accountability can enhance the effectiveness of AI strategies.

### Threats

1. **Environmental Impact:** The rapid growth of AI technology poses a threat due to its environmental impact, emphasizing the need for sustainable practices.
2. **Global Inequality:** Failure to ensure accessibility of AI technologies for low-income nations may exacerbate global inequalities in facing climate-related challenges.
3. **Biases and Privacy Concerns:** Unchecked biases in AI models and privacy concerns related to personal data usage could lead to unintended consequences and public distrust.
4. **Regulatory Challenges:** Policymakers face challenges in developing regulations that balance the advantages of AI in climate change mitigation against environmental impact.
5. **Incomplete Research:** Ethical issues linked to AI and machine learning, which are yet to be fully researched, may pose unforeseen threats in the future.
4.4 Limitations of Using Artificial Intelligence for Mitigating Climate-Related Disasters

Unfortunately, there are some downsides associated with the implementation of artificial intelligence technology that must be considered when applying it as a strategy for mitigating climate change. Namely, artificial intelligence can make mistakes, and human intervention is still required in some cases. Anna Liljedahl, a scientist at the Woodwell Climate Research Center, points out that, “AI is doing the dirty work, but AI is not perfect, so we see it as a first tool, and then the human will come in after and really check and make sure that things make sense and explore the things that AI suggested” (Duffy, 2023).

AI systems also require a lot of energy and power to operate. Storing and processing data for algorithm training—essentially, the 'recipes' computers use for calculations—in data centers or distributed across various cloud facilities with arrays of machines conducting computations, consumes energy (Ekin, 2019). In fact, the ecosystem for information and communications technology, of which data centers are a part, is comparable to aviation in terms of fuel emissions (Ekin, 2019). Swedish researcher Anders Andrae predicts that by 2025, data centers could account for 10% of total global electricity use (Ekin, 2019). “It is time to start thinking about doing AI in a more environmentally friendly way,” says Virginia Dignum, a professor in social and ethical artificial intelligence at Umeå University in Sweden (Ekin, 2019). Ironically, it may help to turn to AI to help solve this challenge. Policymakers, who have begun focusing on establishing guidelines for AI in recent years, should weigh the technology's potential advantages in addressing climate change against its environmental impact when developing regulations (Duffy, 2023).

There are also some ethical issues linked to the usage of AI and machine learning that require consideration, some of which have not even been duly researched yet. One issue arises from biased data used to train these systems, potentially leading to skewed outcomes that don't accurately represent all groups or regions (P.S., 2023). Another concern is the complexity of AI algorithms, making it hard to spot biases or errors, as these systems might lack diverse perspectives, affecting the development of effective adaptation strategies (P.S., 2023). Additionally, ethical dilemmas arise around data privacy and the responsible use of personal information (Jain et al., 2020).

Tech experts also emphasize the necessity of ensuring affordable and accessible AI for low-income nations, particularly those in the Global South (Duffy, 2023). These nations are at the forefront of the climate crisis despite contributing minimally to global pollution (Duffy, 2023).

Addressing these ethical considerations involves several steps. It's crucial to ensure transparency, accountability, and inclusivity in developing and implementing AI systems, which includes diversifying the data used for training, promoting transparency in algorithms, engaging diverse stakeholders in the process, conducting regular ethical audits, and adhering to ethical and legal standards when handling sensitive data (Balasubramaniam et al., 2023). By addressing these concerns, AI-powered climate change strategies can be more inclusive, transparent, and beneficial to all involved (Stahl, 2021; Lacey et al., 2015).
5. Conclusion

Wildfires are intensifying and becoming more frequent around the world, highlighting a need for the development and implementation of more innovative strategies to effectively address and manage this pressing environmental challenge. The European Union has been spending lots of money and resources on tackling wildfires as they arise, but resources are running low, and new strategies must be adopted to help identify and prevent these fires from spreading in the first place. Understanding the four stages of fire management is important for being able to develop targeted strategies to address and respond to wildfires during each step of the way. To prevent wildfires from continuing to worsen, new strategies must be developed to sufficiently respond to all these stages.

Artificial intelligence is an emerging technology that can aid in the progression toward the goal of better wildfire management. AI boasts strengths that surpass human capabilities, giving it the potential to be a key player in this field. However, careful consideration of its drawbacks is necessary during implementation to ensure it adds positive contributions rather than posing additional challenges. Initial pilot projects employing AI are emerging in some of the most severely impacted regions of the world, offering valuable insights into the successes and limitations of using this technology for wildfire management. While AI is still in the early stages of research and development, the sector holds immense potential for growth and expansion, offering a promising solution to manage the environmental, social, and economic impacts of wildfires in the future.

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