
Comprehensive Approaches to Wildfire Management: A Survey

www.surveyx.cn

Abstract

The increasing frequency and severity of wildfires, exacerbated by climate change, necessitates a comprehensive approach to wildfire management. This survey explores the integration of fire suppression strategies, climate change adaptation, policy analysis, fire risk assessment, remote sensing technology, and ecosystem restoration to address these challenges. The deployment of advanced technologies such as artificial intelligence, machine learning, and UAVs has significantly enhanced wildfire detection and response capabilities, demonstrating the transformative impact of these innovations on management effectiveness. The integration of infrastructure, including forest roads, into operational strategies improves fire-fighting efficiency, while hyper-parameter optimized models enhance fuel moisture predictions. The survey highlights the importance of interdisciplinary collaboration, integrating traditional ecological knowledge with scientific approaches, and refining economic evaluation methodologies to inform policy development. Successful case studies underscore the value of community involvement and cost-effective restoration strategies in achieving resilient ecosystems post-wildfire. Future research should focus on leveraging social media data for community response analysis and refining predictive models with advanced space-time structures. By adopting a multifaceted approach, wildfire management practices can be significantly improved, enhancing resilience and effectiveness in the context of climate change.

1 Introduction

1.1 Growing Importance of Wildfire Management

The increasing frequency and severity of wildfires, driven by climate change, underscores the urgent need for enhanced wildfire management strategies. As environmental conditions evolve, implementing adaptive measures becomes crucial [1]. The complexities of wildfire management are further compounded by rapid urbanization and the unpredictable nature of fire spread, necessitating innovative risk mitigation approaches [2].

In Mediterranean regions, wildfires threaten human lives, infrastructure, and ecosystems, emphasizing the necessity for effective management strategies [3]. The role of multispectral indices in wildfire prevention and management has been recognized as vital for addressing these challenges [4]. Moreover, integrating forest road networks into wildfire management enhances fire control operations [5].

The economic and environmental impacts of wildfires, particularly evident in Australia, are profound, with climate change potentially exacerbating their frequency, duration, and severity [6]. Fuel moisture is a critical factor in fire behavior, highlighting the need for comprehensive data assimilation techniques in risk assessment [7]. The surge in scientific literature on climate adaptation presents challenges for evidence synthesis, necessitating advanced tools to complement traditional workflows [8].

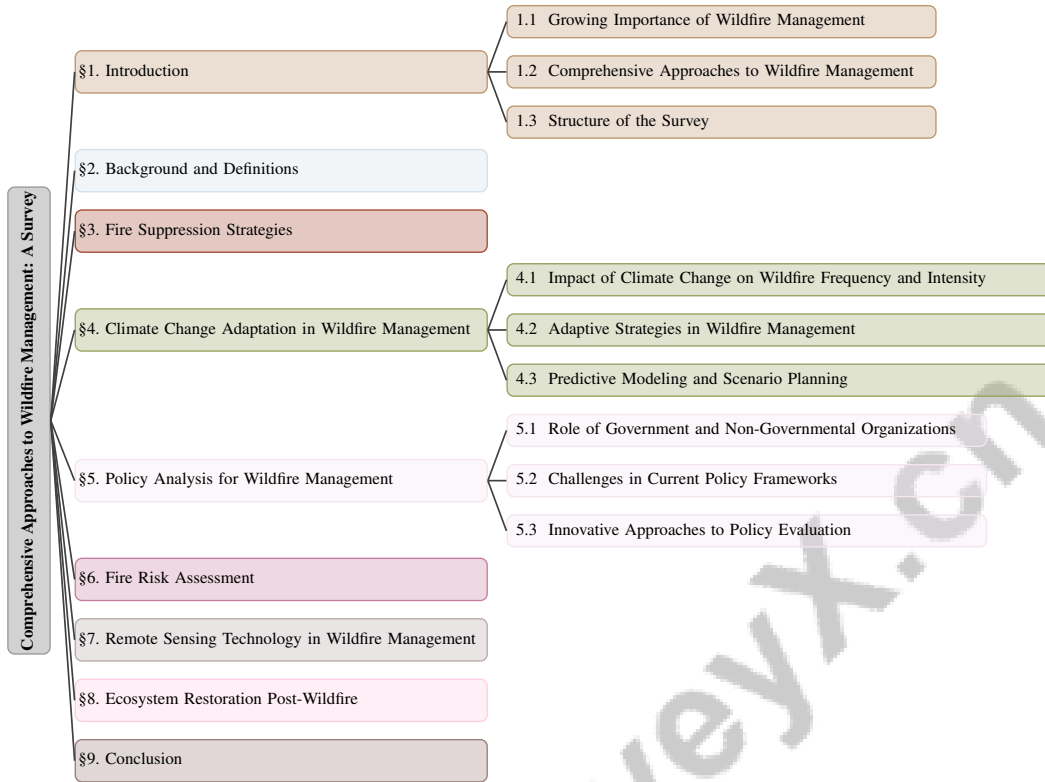


Figure 1: chapter structure

The strategic significance of wildfire management is also reflected in the transboundary haze issue in Southeast Asia, where forest fire spread and firefighting efforts in regions like Dumai, Indonesia, have extensive implications [9]. Additionally, the global land degradation crisis, affecting over 33% of the world's land and billions of livelihoods, underscores the need for effective restoration strategies [10]. Collectively, these factors highlight the growing importance of wildfire management in the context of climate change and its far-reaching impacts.

1.2 Comprehensive Approaches to Wildfire Management

Advancing wildfire management practices requires integrating diverse strategies and technologies to address the challenges posed by climate change. The application of network visualization and natural language processing (NLP) techniques provides a novel approach to synthesizing complex relationships within wildfire management literature, enhancing the understanding of effective strategies [11]. Moreover, the transformative potential of 3D wireless networks in disaster prevention and management highlights the importance of technological integration in improving response capabilities [12].

Ecological restoration is critical for achieving the United Nations Sustainable Development Goals, necessitating its incorporation into comprehensive wildfire management frameworks [13]. This approach is further supported by integrating scientific and indigenous knowledge, community involvement, and financial mechanisms in restoration strategies [10]. Multi-agent reinforcement learning systems, equipped with Graph Neural Network communication layers, facilitate critical information sharing among agents, optimizing decision-making processes in dynamic environments [14].

The integration of UAV-IoT networks significantly enhances wildfire detection probabilities through optimized sensor and UAV deployment, demonstrating the efficacy of advanced technological solutions in early detection and monitoring [15]. Remote sensing technologies have advanced in monitoring meteorological, agricultural, and hydrological droughts, providing valuable data for proactive wildfire management [16]. Additionally, developing susceptibility maps is essential for improving risk management strategies and addressing existing method limitations [3].

Incorporating risk management principles into wildfire decision-making through structured approaches is vital for effective risk mitigation [17]. Multi-agent tracking frameworks that integrate risk-aware behaviors enhance navigation in danger zones, improving operational safety and efficiency [18]. Furthermore, integrating multimodal data, such as camera imagery and weather sensor measurements, into deep learning models like SmokeyNet enhances smoke detection capabilities, showcasing artificial intelligence's potential in improving wildfire management outcomes [19].

The survey emphasizes the need for comprehensive approaches that incorporate forest roads as primary control features in wildfire management, enhancing fire control operations [5]. A synergistic approach involving AI, ML, and 5G technology proposes a proactive framework for wildfire detection and management, reflecting the necessity of integrating cutting-edge technologies into comprehensive strategies [20]. Collectively, these approaches underscore the importance of integrating various strategies and technologies to develop robust and adaptive wildfire management systems.

1.3 Structure of the Survey

This survey provides a comprehensive examination of wildfire management by integrating diverse strategies and technologies. The introduction highlights the increasing importance of wildfire management as a critical response to the challenges posed by climate change, emphasizing the need for improved decision-making processes and risk management strategies, exemplified by programs such as the USDA Forest Service's Risk Management Assistance (RMA) program, which integrates scientific research and interdisciplinary collaboration to enhance wildfire response capabilities [11, 3, 21, 17, 5]. It advocates for a comprehensive approach that encompasses fire suppression strategies, climate change adaptation, policy analysis, fire risk assessment, remote sensing technology, and ecosystem restoration.

The subsequent section, "Background and Definitions," provides an overview of key concepts and terms related to wildfire management, defining essential terms such as wildfire management, fire suppression strategies, climate change adaptation, policy analysis, fire risk assessment, remote sensing technology, and ecosystem restoration while discussing their interconnections.

Following this, the survey explores "Fire Suppression Strategies," examining both traditional methods and modern technological advancements. This analysis addresses the challenges and limitations of existing strategies for policy analysis, evaluating the effectiveness of various AI tools and methodologies. By assessing the performance of AI systems like Gemini 1.5 Pro and Claude 3 Opus in extracting relevant information from complex policy documents and evaluating models like GPT-4o in evidence synthesis, the study provides insights into the strengths and weaknesses of current approaches. Furthermore, it emphasizes the necessity for ongoing research and the development of frameworks that enhance reproducibility and operational effectiveness in policy analysis [11, 8, 22, 23, 24].

The section on "Climate Change Adaptation in Wildfire Management" examines the impact of climate change on wildfire frequency and intensity, discussing strategies for adapting wildfire management practices and highlighting the role of predictive modeling and scenario planning.

"Policy Analysis for Wildfire Management" evaluates existing policies and the roles of government and non-governmental organizations in policy formulation and implementation. The study employs advanced AI techniques, specifically large language models, to analyze complex policy documents and recommends targeted improvements based on the findings [22, 11, 23].

The "Fire Risk Assessment" section explores methods and tools for assessing fire risk, emphasizing data analysis and modeling's importance in predicting fire risk and integrating risk assessment into management strategies.

In "Remote Sensing Technology in Wildfire Management," the paper discusses remote sensing technology's applications in monitoring and managing wildfires. Advances in satellite and unmanned aerial vehicle (UAV) technologies have significantly transformed remote sensing capabilities, enabling ultra-high spatial and spectral resolution data collection. This progress facilitates a broader range of applications, from drought monitoring to wildfire detection. However, integrating diverse sensing systems presents challenges in ensuring data quality and consistency. Analyzing these advancements reveals the benefits of enhanced data collection and the complexities involved in standardizing procedures for effective remote sensing practices [11, 25, 15, 16, 26].

The survey investigates "Ecosystem Restoration Post-Wildfire," outlining various strategies for effective ecosystem restoration. It emphasizes restoring biodiversity and ecosystem services, integrating traditional ecological knowledge and community engagement to enhance restoration efforts. The discussion includes challenges posed by land degradation and the importance of adaptive management frameworks that incorporate diverse perspectives and real-time data to foster resilience in socio-ecological systems. Additionally, it underscores the significance of aligning restoration initiatives with the United Nations' Sustainable Development Goals, particularly during the UN Decade on Ecosystem Restoration, to ensure comprehensive and inclusive approaches to restoring ecosystems affected by wildfires [27, 28, 29, 10, 5]. It highlights successful case studies and best practices.

Finally, the "Conclusion" summarizes the key findings of the survey, emphasizing the importance of a comprehensive approach to wildfire management. The findings indicate critical avenues for future research and policy formulation, highlighting the necessity of integrating diverse strategies and technologies to create resilient and adaptive systems capable of addressing complex challenges, such as climate change and disaster management. This integration is vital for facilitating interdisciplinary collaboration and enhancing policy analysis efficiency through advanced tools like Natural Language Processing and AI, ultimately leading to more effective solutions in climate adaptation and emergency response [11, 12, 22, 1, 23]. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Defining Wildfire Management and Challenges

Wildfire management is a complex discipline aimed at minimizing the adverse impacts of wildfires on human safety, infrastructure, and ecosystems. It employs advanced strategies like the USDA Forest Service's Risk Management Assistance (RMA) program, which enhances decision-making through scientific research and tools during wildfire events. This field involves multi-criteria decision-making to balance wildfire risks against ecosystem services such as timber and carbon storage, promoting stakeholder collaboration and adaptation to emerging challenges [28, 17]. Key components include fire suppression, climate change adaptation, policy analysis, fire risk assessment, remote sensing, and ecosystem restoration, all vital for addressing the complexities of wildfire management amid climate change and shifting land-use patterns.

A major challenge is the increasing frequency and intensity of wildfires, especially in the United States, posing threats to life, property, and the environment [20]. Current practices are insufficient, necessitating precise modeling techniques, particularly in Australia, where dynamic wildfire behavior requires accurate prediction [6]. Decision-making is further complicated by the need to balance immediate suppression costs with long-term ecological benefits, a challenge that varies among stakeholders [30].

Integrating forest road networks into wildfire response planning is a critical yet underutilized strategy for enhancing operational efficiency [5]. Accurately mapping burned areas, especially small fire scars, remains challenging, as seen in Chile, where current methodologies are inadequate, highlighting the need for scalable detection approaches [31]. In Dumai, Indonesia, uncontrolled forest fires are exacerbated by slash-and-burn practices and conducive climatic conditions [9], necessitating comprehensive strategies that address both human activities and environmental factors.

The complexity of wildfire management is intensified by the high dimensionality of hyperspectral data, which complicates modeling relationships between spectral wavelengths and ecological traits, leading to classification inaccuracies [32]. Early wildfire detection is crucial for mitigating environmental and human safety impacts, yet remains a significant challenge [2].

Public perceptions and responses to wildfire threats, particularly in real-time, are poorly understood, hindering effective disaster management and emergency response [33]. Addressing these challenges requires integrating advanced technological solutions, robust communication systems, comprehensive data analysis, and understanding the interactions between land use, fire suppression, and ecosystem dynamics. Additionally, the economic valuation of climate adaptation efforts presents challenges in estimating costs and benefits amidst uncertainties, complicating effective strategy formulation [34]. These efforts are crucial for developing strategies to mitigate wildfire impacts in an era marked by climate change and rapid environmental transformation.

2.2 Interconnections Between Land-Use Change and Fire Suppression

Land-use change significantly influences fire suppression strategies by altering vegetation patterns, fuel availability, and landscape connectivity. Urbanization, agricultural expansion, and deforestation disrupt natural fire regimes, reducing the efficacy of traditional methods. This is evident in the Mediterranean regions of the Iberian Peninsula, where land-use policies can mitigate the adverse effects of fire suppression on ecosystems and biodiversity. Research suggests that land abandonment and High Nature Value farming can enhance functional diversity, highlighting adaptive land management's importance in addressing evolving fire dynamics [29, 21]. As landscapes fragment, managing fire-prone areas becomes more complex, necessitating adaptive strategies.

Comprehensive fire risk assessment models are essential to address challenges posed by land-use change. Current benchmarks rely on complex geospatial data and specialized knowledge, limiting their general applicability [35]. These models, categorized into statistical, machine learning, multi-criteria decision-making, and ensemble models, depend on data availability and harmonization across landscapes, as shown by the need for a pan-European fuel map server [36].

The accuracy of fire risk assessments is hindered by limitations in detection methods, which often show high commission and omission errors, particularly in small fire detection due to low-resolution imagery and ineffective algorithms [31]. These challenges highlight the necessity for scalable approaches that effectively integrate land-use change data into fire suppression strategies.

In examining the evolution of fire suppression strategies, it is essential to recognize the distinct approaches that have emerged over time. As illustrated in Figure 2, the hierarchical categorization of these strategies delineates between traditional methods and technological advancements. Traditional methods encompass both direct and indirect techniques, which have been foundational in fire management. Conversely, technological advancements highlight the innovative technologies, advanced computational methods, and integration strategies that are increasingly being utilized for enhanced wildfire management. This dual framework not only reflects the progression in fire suppression tactics but also underscores the importance of adapting to new challenges posed by changing environmental conditions.

3 Fire Suppression Strategies

3.1 Traditional Fire Suppression Methods

Traditional fire suppression methods remain fundamental in wildfire management, utilizing direct and indirect techniques such as constructing firebreaks, deploying water and chemical retardants, and conducting controlled burns. The accessibility of forest roads enhances the effectiveness of these methods by improving firefighting crew responsiveness [5]. However, these strategies often emphasize immediate fire control, potentially compromising long-term ecological sustainability. For example, Portugal's reliance on suppression tactics, coupled with insufficient forest management and funding for preventive measures, highlights the limitations of traditional approaches [21]. The integration of Risk Management Assistance (RMA) tools can enhance these methods by offering structured risk mitigation strategies, although their success varies by context [17].

These traditional methods are assessed within various land-use management frameworks, such as business-as-usual and High Nature Value approaches, which, alongside different fire suppression levels, significantly affect ecosystem functional diversity [29]. Cellular automata models simulate fire spread, providing insights into fire dynamics and informing the refinement of traditional techniques [9].

As illustrated in Figure 3, the hierarchical categorization of traditional fire suppression methods highlights key techniques, their limitations, and enhancements, as well as their assessment and impact on wildfire management. This figure serves to contextualize the discussion by visually representing the complexities and interdependencies inherent in these approaches, thereby enriching our understanding of their role in effective wildfire management.

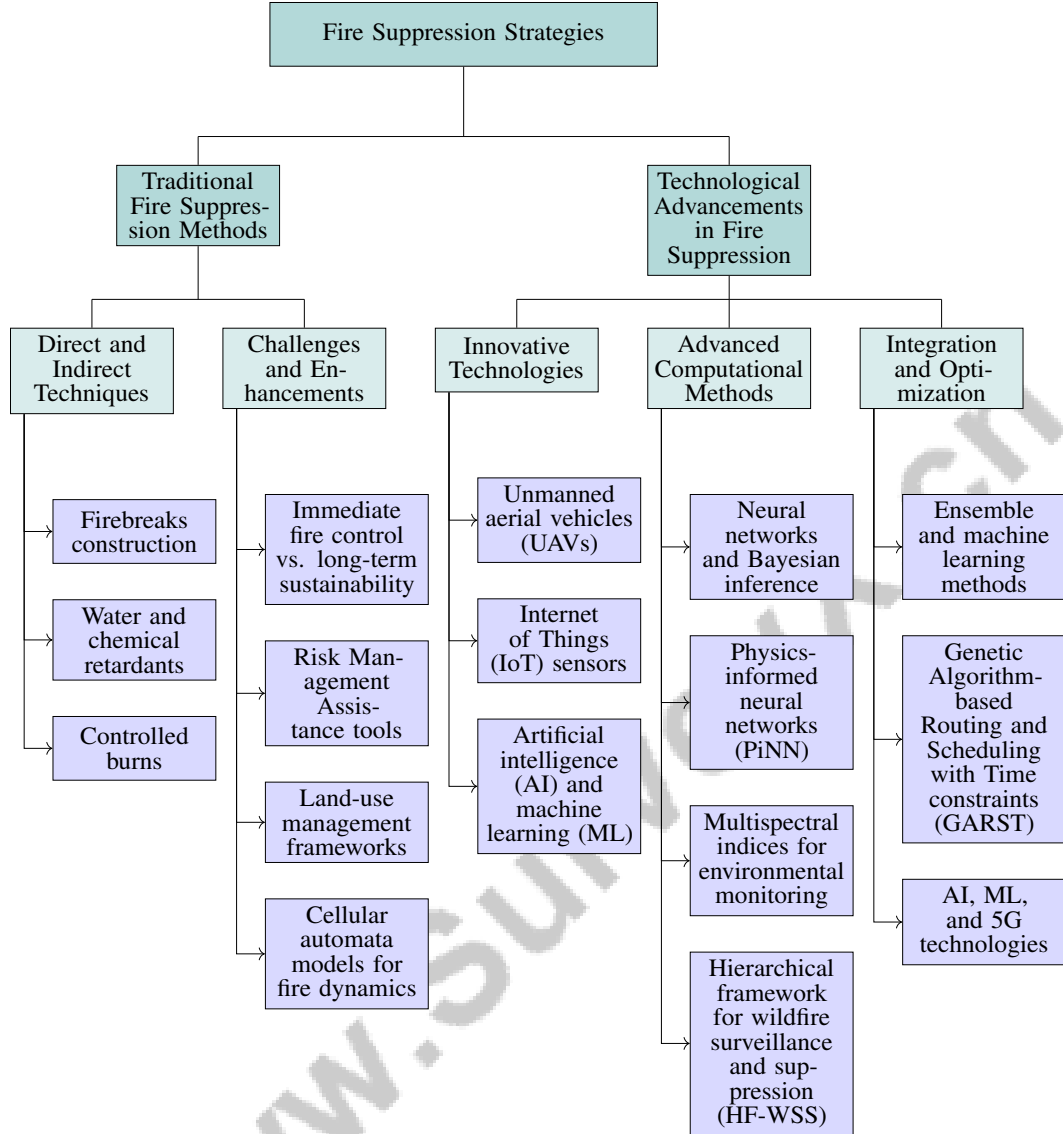


Figure 2: This figure illustrates the hierarchical categorization of fire suppression strategies, distinguishing between traditional methods and technological advancements. Traditional methods encompass direct and indirect techniques, while technological advancements focus on innovative technologies, advanced computational methods, and integration strategies for enhanced wildfire management.

3.2 Technological Advancements in Fire Suppression

Technological advancements have revolutionized fire suppression strategies, integrating innovative technologies to improve wildfire management efficiency. Tools such as unmanned aerial vehicles (UAVs) and Internet of Things (IoT) sensors facilitate real-time monitoring and rapid response, crucial for controlling wildfire spread and impact [15]. Artificial intelligence (AI) and machine learning (ML) further enhance suppression methodologies. For instance, SmokeyNet utilizes multimodal data, including imagery and weather conditions, to improve smoke detection [19], while graph convolutional neural networks combined with probabilistic models provide accurate predictions of fire dynamics across varied terrains [6].

Advanced neural network architectures, such as ResNet, integrated with Bayesian inference-based path planning algorithms, enhance target detection capabilities, facilitating timely fire front iden-

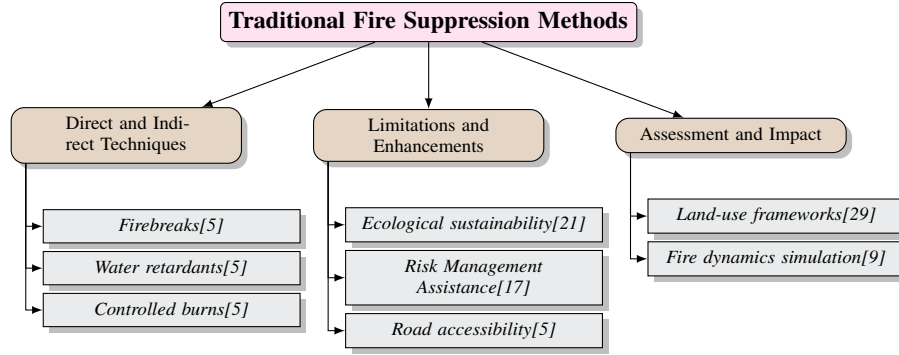


Figure 3: This figure illustrates the hierarchical categorization of traditional fire suppression methods, highlighting key techniques, their limitations, and enhancements, as well as their assessment and impact on wildfire management.

tification and intervention [37]. Physics-informed neural networks (PiNN) represent a significant advancement, training on synthetic and empirical data to understand wildfire behaviors and model parameters [38].

Multispectral indices have significantly advanced environmental monitoring, enabling precise evaluations of fire-prone areas [4]. The hierarchical framework for wildfire surveillance and suppression (HF-WSS) employs an innovative hierarchical approach, optimizing coordination between manned and unmanned aircraft [39]. Integrating real-time data from UAVs and satellites into dynamic planning systems enhances escape route formulation, improving safety for firefighters and communities [40].

Ensemble and machine learning methods offer superior accuracy in predicting fire risks and hazards compared to traditional techniques, underscoring the importance of advanced computational methods in modern fire suppression [41]. Recent developments in machine learning algorithms and multispectral imaging technologies have improved detection accuracy and response times [2]. The Max Relevance Max Synergy (MRMS) algorithm optimizes spectral band selection, enhancing classification accuracy through a novel filtering approach [32]. AI, ML, and 5G integration has significantly improved wildfire detection and response efficiency, surpassing traditional methods [20].

John et al. (2024) introduce a Genetic Algorithm-based Routing and Scheduling with Time constraints (GARST), optimizing UAV routing and scheduling for wildfire suppression, thus enhancing operational efficiency [42]. The integration of AI, ML, and 5G technologies marks a transformative evolution in wildfire detection and management, promoting proactive strategies like AI-enabled remote sensing and multimodal smoke detection systems. UAVs with advanced sensors further improve monitoring and response capabilities, facilitating effective management throughout the wildfire lifecycle—from prevention and real-time response to recovery efforts. These advancements aim to mitigate wildfires' impacts on ecosystems and communities while enhancing wildfire management resilience amidst escalating climate challenges [20, 19, 43].

4 Climate Change Adaptation in Wildfire Management

4.1 Impact of Climate Change on Wildfire Frequency and Intensity

Climate change significantly influences wildfire frequency and intensity by altering environmental factors such as temperature, precipitation, and atmospheric conditions. Rising global temperatures and changing precipitation patterns extend fire seasons and worsen fire conditions, thereby increasing the likelihood and severity of wildfires [44]. The inherent uncertainties in climate forecasts, particularly regarding temperature and precipitation, complicate wildfire risk predictions, underscoring the need for adaptive management strategies to manage these uncertainties [45].

The complexity of fire dynamics demands sophisticated modeling techniques that consider interacting elements like wind, vegetation, and local environmental conditions. Existing models often struggle to accurately predict fire behavior, especially in regions like Australia, where both moderate and extreme

fire incidents occur frequently. Integrating message passing neural networks, which combine global reanalysis data with localized observations, enhances predictive capabilities for localized weather conditions [46].

Remote sensing technology is crucial in wildfire management, yet current methodologies face challenges in detection speed and reliability, particularly under adverse conditions [15]. The creation of wildfire susceptibility maps using techniques like the Random Forest Classifier helps in understanding and managing wildfire risks seasonally, as demonstrated in national-scale studies in Italy [3]. However, the spatial sparsity of remote automated weather stations (RAWS) complicates acquiring direct moisture observations, critical for accurate fire risk assessments [7].

Human detection methods remain inadequate in wildfire management, often delaying response efforts [19]. The integration of UAV and IoT networks enhances detection and monitoring capabilities, providing real-time data essential for adaptive management [40]. The rapid and unpredictable spread of fire and smoke further necessitates dynamic and responsive strategies for effective route planning [40].

The interrelations among various drought types—meteorological, agricultural, hydrological, and socio-economic—complicate wildfire management, as each type uniquely influences fire risk [16]. Understanding these relationships is essential for devising comprehensive adaptation strategies that mitigate climate change impacts on wildfire dynamics. Additionally, climate change exacerbates land degradation, increasing wildfire risks and underscoring the need for multifaceted adaptation approaches [10].

In regions like Portugal, where human activities predominantly drive fires, there is significant potential to adapt wildfire management practices to mitigate anthropogenic influences [21]. Innovative approaches, such as stochastic simulations, can effectively assess safety and enhance management strategies [47].

Figure 4 illustrates the impact of climate change on wildfire frequency and intensity, highlighting key environmental factors, technological solutions, and management strategies. It emphasizes the role of rising temperatures, changing precipitation patterns, and wind dynamics, while also showcasing technological advancements like remote sensing and UAV-IoT networks. Additionally, it underscores the importance of adaptive management and understanding drought interrelations for effective wildfire management. These insights collectively emphasize the necessity for a holistic wildfire management approach that integrates advanced modeling, robust detection systems, and adaptive strategies to confront climate change challenges.

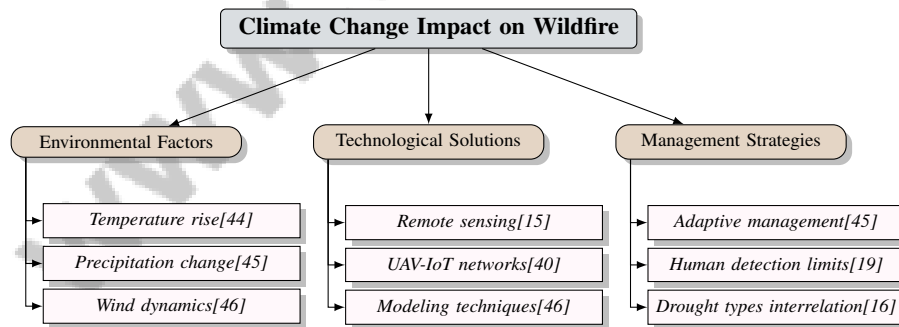


Figure 4: This figure illustrates the impact of climate change on wildfire frequency and intensity, highlighting key environmental factors, technological solutions, and management strategies. It emphasizes the role of rising temperatures, changing precipitation patterns, and wind dynamics, while also showcasing technological advancements like remote sensing and UAV-IoT networks. Additionally, it underscores the importance of adaptive management and understanding drought interrelations for effective wildfire management.

4.2 Adaptive Strategies in Wildfire Management

Adapting wildfire management strategies to climate change impacts requires a multifaceted approach incorporating advanced technologies, probabilistic modeling, and interdisciplinary collaboration. Accurate estimation of fuel moisture content is crucial for predicting fire behavior. Integrating spatial

variability and environmental factors into estimation methods enhances the accuracy of fuel moisture assessments compared to traditional techniques [7]. Such advancements in data precision are vital for developing responsive adaptive strategies.

The incorporation of machine learning (ML) and artificial intelligence (AI) into wildfire management has shown significant promise, particularly in improving fire risk assessments and facilitating proactive detection and management [20]. However, challenges remain in handling complex tasks, necessitating the refinement of model capabilities to meet high-expertise requirements [8]. Addressing biases in ML algorithms stemming from non-representative datasets and promoting interdisciplinary collaboration are crucial for merging traditional ecological knowledge with scientific methods, thereby enhancing wildfire management adaptability [27].

Adopting hierarchical frameworks improves coordination between manned and unmanned aircraft, enhancing flexibility in suppression strategies and providing real-time insights into wildfire dynamics [39]. Models that propagate uncertainty in airborne laser scanning (ALS) and ground-based data enable robust quantification of uncertainty in hectare-scale carbon stock estimates, essential for understanding wildfires' ecological impacts and informing adaptive management practices [48].

Additionally, joint multivariate functional modeling captures relationships between multivariate continuous traits and functional reflectance data in response to environmental factors, offering a comprehensive perspective on wildfire dynamics [49]. The use of graph neural networks (GNNs) transforms climate and wildfire data into graph representations, improving the handling of long-range dependencies and missing data, which is critical for global wildfire prediction and management [50].

The MRMS method, which evaluates the relevance of individual bands and their synergy, ensures that selected bands provide complementary information to enhance classification performance [32]. Genetic algorithm-based routing and scheduling facilitate timely interventions to minimize wildfire damage, addressing the urgent need for adaptive strategies in wildfire management [42].

Investments in climate adaptation, as highlighted in economic assessments, can mitigate future costs and bolster resilience, which is vital for effective wildfire management [34]. By integrating these advanced methodologies and fostering interdisciplinary collaboration, adaptive strategies can effectively tackle the complexities and uncertainties posed by climate change, ultimately enhancing the resilience and efficacy of wildfire management practices.

4.3 Predictive Modeling and Scenario Planning

Predictive modeling and scenario planning are integral to climate adaptation strategies in wildfire management, providing essential tools for anticipating fire behavior and guiding strategic decision-making. Advanced machine learning techniques, such as the adaptive bias correction method, improve the precision of subseasonal forecasts by integrating dynamical forecasts with observational data, thus refining predictions of wildfire frequency and intensity. This approach is vital for comprehending evolving wildfire dynamics and enhancing management responses [4].

The application of graph convolutional network-long short-term memory (GCN-LSTM) models has demonstrated superior predictive accuracy over baseline models by effectively addressing challenges posed by null oceanic data and long-range dependencies. This advancement illustrates the potential of complex machine learning models to enhance predictability and management of global wildfire risks [50]. Furthermore, the joint multivariate functional modeling approach, which models a vector of traits alongside functional reflectance spectra while considering environmental predictors, provides a comprehensive framework for understanding intricate interactions between environmental factors and wildfire dynamics [49].

Incorporating AI and unmanned aerial vehicles (UAVs) into predictive modeling and scenario planning significantly enhances decision-making and operational efficiencies. AI-enabled systems facilitate real-time data processing and scenario analysis, which are crucial for effective wildfire management. The integration of belief-based deep reinforcement learning models enhances UAV capabilities by enabling dynamic updates of fire state probabilities in unobserved regions. This allows UAVs to make informed decisions in real-time, even in partially observable environments, by utilizing a Bayesian framework to adjust ignition probabilities for grid areas within their limited field of view. Consequently, UAVs can more effectively track wildfire progression and optimize path planning, improving their performance in active wildfire monitoring scenarios [51, 52, 53, 43].

Future research should prioritize developing hybrid approaches that integrate multiple indices and data sources, alongside exploring emerging trends in remote sensing technology. These initiatives are essential for enhancing the scalability and precision of wildfire predictions, ensuring that adaptive strategies remain responsive and effective in the face of changing environmental conditions [4].

Collectively, advancements in predictive modeling and scenario planning underscore the importance of integrating cutting-edge technologies and methodologies to bolster the resilience and effectiveness of climate adaptation strategies in wildfire management. By leveraging advanced technologies such as AI, ML, and 5G, wildfire management practices can be significantly improved, enabling more proactive and informed responses to the escalating challenges posed by climate change. These tools facilitate enhanced detection, active monitoring, and efficient response mechanisms, including the use of drones and IoT devices, which collectively contribute to superior prevention and management strategies. Structured decision-making frameworks, exemplified by the Risk Management Assistance program initiated by the USDA Forest Service, allow for the incorporation of scientific research and risk assessment into strategic planning, further optimizing wildfire management efforts [17, 20, 11, 5].

5 Policy Analysis for Wildfire Management

The synergy between policy development and execution is vital for wildfire management, especially as wildfires become more frequent and severe. This section explores the roles of governmental and non-governmental organizations (NGOs) in shaping wildfire management policies, focusing on their collaborative efforts and the impacts of their involvement.

5.1 Role of Government and Non-Governmental Organizations

Governmental and non-governmental organizations (NGOs) are instrumental in creating and executing wildfire management policies. Governments primarily fund and support climate adaptation initiatives, which are crucial for developing effective wildfire management strategies [34]. This often involves integrating advanced technologies, such as UAVs, into fire suppression policies to improve the efficiency and responsiveness of wildfire operations [42]. UAVs enhance real-time data collection and monitoring, optimizing resource routing and scheduling for better operational outcomes.

NGOs, on the other hand, advocate for sustainable practices and promote community-based wildfire management approaches. Their grassroots initiatives complement governmental efforts, particularly in addressing socio-spatial disparities in public awareness and resilience. By fostering community engagement, NGOs develop strategies tailored to the socio-economic and demographic needs of diverse regions, enhancing community resilience to wildfire threats. Research highlights disparities in public awareness and response to wildfires, influenced by factors like racial/ethnic composition and employment rates. By incorporating local knowledge and perspectives, NGOs facilitate more effective wildfire management strategies that improve adaptive capacity and ensure equitable interventions [20, 27, 21, 17, 33].

As illustrated in Figure 5, the hierarchical structure of wildfire management strategies emphasizes the distinct yet interconnected roles of governmental bodies, NGOs, and collaborative efforts in enhancing wildfire management. Governmental roles focus on funding, technology integration, and methodological advancements, while NGOs contribute through community engagement and advocating for equitable and sustainable practices. Collaboration between these entities is crucial for resolving policy implementation conflicts, especially regarding lightning-caused wildfires, where multiple stakeholder interests must be balanced. By leveraging collective expertise and resources, these organizations can create policies that reflect diverse perspectives and integrate advanced methodologies, such as Natural Language Processing and machine learning, to enhance sustainable management practices. This collaborative approach encourages the incorporation of traditional ecological knowledge, community engagement, biodiversity conservation, and ecosystem resilience, aligning with the United Nations' Sustainable Development Goals [11, 27, 22, 23, 24].

5.2 Challenges in Current Policy Frameworks

Current wildfire management policy frameworks encounter several significant challenges. A major issue is the high computational cost and time associated with traditional Regional Climate Models (RCMs) for downscaling, limiting the generation of large climate simulation ensembles necessary for

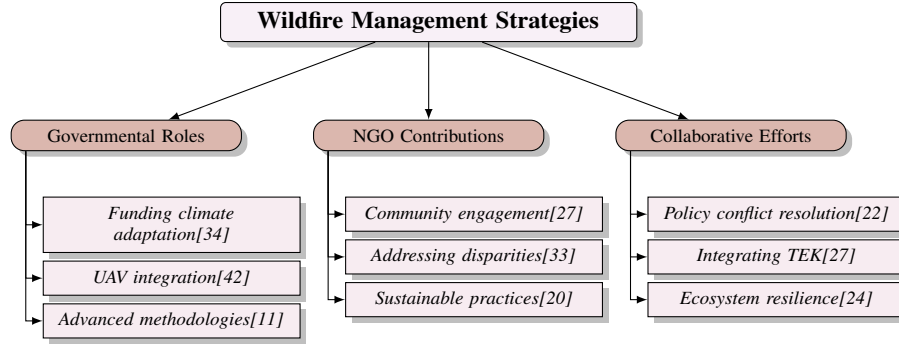


Figure 5: This figure illustrates the hierarchical structure of wildfire management strategies, highlighting the roles of governmental bodies, NGOs, and collaborative efforts in enhancing wildfire management. Governmental roles focus on funding, technology integration, and methodological advancements. NGOs contribute through community engagement and advocating for equitable and sustainable practices. Collaborative efforts emphasize resolving policy conflicts and integrating traditional ecological knowledge for ecosystem resilience.

comprehensive policy analysis [54]. This limitation impedes the development of robust strategies for predicting and managing future wildfire scenarios.

Inadequacies in coordination and optimization within existing wildfire management methods further exacerbate resource inefficiencies, underscoring the need for improved policy frameworks [39]. Managing multiple agents in dynamic environments often results in infeasibility in optimization problems, especially when robots inadvertently enter danger zones due to localization and actuation uncertainties [18].

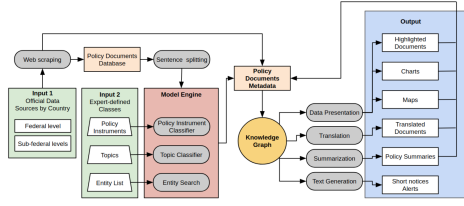
Reliance on expert evaluations for policy assessment presents another challenge, as these benchmarks often lack diversity and scalability. Utilizing diverse input from non-expert crowds can enhance the inclusivity and effectiveness of policy assessments [55]. However, the limited availability of labeled data in the forestry policy domain constrains existing supervised knowledge extraction methods, hindering comprehensive policy framework development [56].

High-fidelity simulations, while valuable for accurate modeling, are limited by their computational cost, affecting ensemble size and scalability in policy frameworks [57]. Additionally, variability in weather data quality and availability introduces inconsistencies in policy outcomes, leading to unreliable assessments [19].

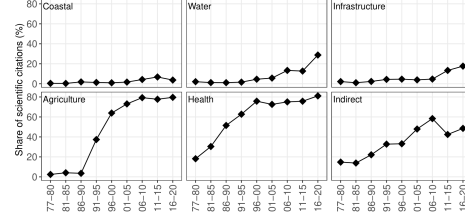
The resilience of fires, particularly in peatland areas with underground burning, poses significant challenges to conventional firefighting efforts, necessitating policy frameworks that account for such complexities [9]. Furthermore, the increased computational cost associated with complex data fusion methods limits their applicability in resource-constrained environments, affecting the integration of advanced technologies into policy frameworks [58].

Finally, reliance on human judgment in selecting input parameters for simulations can introduce biases and inaccuracies, complicating reliable safety assessments and highlighting the need for more objective, data-driven approaches in policy formulation [47]. Addressing these challenges requires developing flexible and adaptive policy frameworks that effectively incorporate advanced technologies and diverse data sources to enhance the resilience and effectiveness of wildfire management systems.

As illustrated in Figure 6, exploring the complexities of wildfire management necessitates a thorough examination of existing policy frameworks and their challenges. The first subfigure, "A Flowchart of a Document Processing System," demonstrates the intricate process of handling and generating outputs from official data sources across various governmental levels. This system relies on a model engine that processes data inputs categorized by federal and sub-federal sources alongside expert-defined classes such as policy instruments and topics, underscoring the challenge of integrating diverse data sources and expert knowledge into cohesive policy frameworks. The second subfigure presents line graphs depicting the evolution of scientific citations across sectors like Coastal, Water, and Agriculture over time, emphasizing the dynamic nature of scientific research and its implications for policy development. Such shifts in scientific focus can significantly impact policy effectiveness,



(a) A Flowchart of a Document Processing System[22]



(b) The image shows a series of line graphs with different titles and data points representing the share of scientific citations over time for various sectors.[1]

Figure 6: Examples of Challenges in Current Policy Frameworks

highlighting the multifaceted challenges in formulating effective wildfire management policies that require a comprehensive approach integrating diverse data and adapting to evolving scientific insights [22, 1].

5.3 Innovative Approaches to Policy Evaluation

Benchmark	Size	Domain	Task Format	Metric
GAMI-GPT-4o[8]	1,682	Climate Adaptation	Information Extraction	Precision, Recall
CCAPM[55]	23,280	Climate Change Adaptation	Policy Assessment	Median Assessment Value
RSI-AE[59]	31,500	Remote Sensing	Scene Classification	Fooling Rate
PEFMS[36]	1,800	Fire Risk Assessment	Fire Behavior Modeling	Accuracy, F1-score
EO14110[23]	20,000	Policy Analysis	Question Answering	F1 Score, Precision
ChatEarthNet[60]	173,488	Remote Sensing	Image Captioning	Accuracy, F1-score
FireRisk[35]	91,872	Fire Risk Assessment	Image Classification	Accuracy, F1-score

Table 1: This table presents a comprehensive overview of various benchmark datasets utilized in policy evaluation and climate adaptation research. It details the size, domain, task format, and evaluation metrics for each benchmark, highlighting their relevance in advancing innovative approaches to policy assessment and management.

Innovative approaches to policy evaluation are crucial for enhancing the effectiveness of wildfire management strategies, particularly amid increasing climate variability. Systematic evidence synthesis methods provide a robust framework for evaluating adaptation responses to climate change, ensuring that policies are evidence-based and contextually relevant [8]. This emphasizes comprehensive data collection and analysis, crucial for informed policy decisions. Table 1 provides a detailed overview of benchmark datasets that are instrumental in enhancing policy evaluation processes, particularly within the context of climate adaptation and wildfire management strategies.

Advanced machine learning models, such as those employing echo state networks, have demonstrated superior forecasting performance in capturing wildfire spread dynamics, offering reliable uncertainty quantification to improve policy evaluation processes [61]. Additionally, probabilistic models for emergency management enhance evacuation strategies under uncertainty, representing a significant advancement in policy evaluation by addressing the complexities of wildfire events [55].

Crowdsourcing has emerged as a promising tool in policy evaluation, with studies indicating that non-expert crowds can replicate expert assessments in policy design, enhancing the efficiency and diversity of evaluation processes [55]. The Decentralized Resource Allocation Algorithm (DRAA), which dynamically allocates resources based on workload, aligns with the need for resource-efficient policy evaluation and management in wildfire contexts [62].

The integration of responsible AI frameworks, such as the IEEE 7010 well-being impact assessment, offers a comprehensive approach to addressing social and ethical issues in policy evaluation, surpassing narrower methodologies [24]. Furthermore, the recommendation of a decision support system (DSS) aids in real-time decision-making during wildfire incidents, underscoring the transformative role of technology in policy evaluation [20].

Future research should focus on refining adaptive bias correction methods and exploring their application in diverse forecasting contexts, including improved integration with dynamical modeling techniques, which are vital for advancing policy evaluation frameworks [49]. By leveraging these innovative approaches, policymakers can develop more adaptive and robust strategies that effectively address the challenges posed by climate change and evolving environmental conditions.

6 Fire Risk Assessment

Fire risk assessment is crucial in wildfire management, guiding strategic decisions and operational responses. Understanding fire hazards involves exploring methodologies and tools used in these assessments, which are essential for developing adaptive management strategies to address the dynamic challenges posed by wildfires. The following subsection highlights specific methods and tools employed in fire risk assessment, emphasizing their role in enhancing predictive capabilities and informing proactive measures against fire threats.

6.1 Methods and Tools for Fire Risk Assessment

Effective fire risk assessments rely on diverse methods and tools to predict and mitigate potential fire hazards accurately. Advanced technologies, such as 3D wireless networks, significantly enhance data collection and analysis, enabling real-time monitoring of fire risks [12]. The Forest Fire Risk Evaluation Framework (FFREF) exemplifies sophisticated approaches, integrating UAV imagery with multi-stage object detection algorithms and color mapping techniques to improve risk evaluation precision. The UAV-IoT network's capacity to support up to 1 million IoT devices per square kilometer by 2025 underscores the potential for extensive sensor deployment in fire risk assessments [15].

Remote sensing data, combined with machine learning algorithms and geospatial datasets, underpin comprehensive fuel mapping efforts, as demonstrated by the pan-European fuel map server detailing canopy and surface fuel models essential for accurate fire risk modeling [36]. The FireRisk dataset, comprising 91,872 labeled images across seven fire risk classes, serves as a robust resource for training and validating fire risk models, enhancing predictive capabilities [35].

Research identifies four frameworks for fire risk assessment methodologies: statistical and data-driven models, machine learning models, multi-criteria decision-making models, and ensemble models, each with strengths and limitations [41]. Automating the analysis of trade-offs between wildfire risk and ecosystem services using stand-level data integrates ecological considerations into fire risk assessments [28].

The Genetic Algorithm-based Routing and Scheduling with Time constraints (GARST) optimizes UAV routes for wildfire mitigation, enhancing operational efficiency [42]. However, challenges persist, particularly regarding data availability on fire causes and prevention effectiveness, which can lead to fragmented understanding in regions like Portugal [21]. Addressing these gaps requires ongoing development and integration of advanced technological solutions and data-driven approaches to improve fire risk assessment accuracy and efficacy.

6.2 Data Analysis and Modeling Techniques

Data analysis and modeling techniques are vital for improving fire risk prediction accuracy and reliability, informing effective wildfire management strategies. Machine learning methodologies, such as Deep Slow Feature Analysis (DSFA), enhance change detection in multi-temporal imagery by capturing temporal dependencies and relevant features [63]. These techniques are essential for monitoring dynamic environmental conditions and predicting potential fire hazards.

Advanced computational methods, including neural network-based parameter estimation, model complex, non-linear relationships within large datasets, offering superior predictive capabilities compared to traditional techniques [6]. The segmentation of satellite images into superpixels, followed by classification through fully connected layers, provides a comprehensive evaluation of ecosystem services, crucial for understanding wildfire ecological impacts [64].

The SatDiffMoE method, evaluated on datasets like fMoW and WorldStrat, illustrates the potential of advanced modeling techniques to enhance perceptual quality and realism in data analysis tasks,

ensuring high-quality fire risk predictions [65]. Robust evaluation metrics, including Mean Squared Error (MSE), ROC AUC scores, and overall accuracy assessed through spatial cross-validation, provide frameworks for model effectiveness evaluation [3].

The Dynamic Resource Allocation Algorithm (DRAA) optimizes resource usage during large-scale data processing, enhancing computational efficiency and resource management in fire risk assessments [62]. Integrating data from multiple satellite sources through models like DFGP addresses challenges in analyzing spatio-temporal data from varying resolutions, refining predictive capabilities [58].

Incorporating dead fuel moisture observations into predictive frameworks using trend surface models and Kalman filtering exemplifies the integration of observational data into fire risk assessments, improving prediction accuracy [63]. The effectiveness of these methods is often evaluated by comparing simulation results with recorded fire spread, focusing on accuracy and the effectiveness of different firefighting strategies [9].

The integration of advanced computational techniques, including data analysis, modeling, and machine learning, significantly enhances fire risk prediction frameworks. These methodologies facilitate developing sophisticated models that simulate wildfire behavior, assess fire susceptibility, and optimize resource allocation, ultimately improving wildfire management strategies. Recent studies demonstrate the use of high-fidelity ensemble simulations and comprehensive remote sensing datasets to inform decision-making processes, reducing response times and mitigating the destructive impacts of wildfires on ecosystems and communities [57, 51, 20, 35, 3].

6.3 Integration of Risk Assessment into Management Strategies

Integrating risk assessment into wildfire management strategies is essential for enhancing decision-making efficacy and improving the resilience of fire management systems. A comprehensive approach to risk assessment employs data-driven models that simulate fire spread based on relevant covariates, providing critical insights into potential fire dynamics [51]. These models highlight the importance of incorporating risk assessment into management strategies by offering predictive capabilities that inform strategic planning and operational decisions.

Figure 7 illustrates the integration of risk assessment into wildfire management strategies, highlighting key components such as data-driven models, strategic incorporation stages, and advanced frameworks. Each component contributes to enhancing decision-making and improving resilience in fire management systems.

The availability and accuracy of geospatial data are crucial for effective fire risk assessment, exemplified by the development of a pan-European fuel map server that enhances decision-making capabilities in wildfire management across Europe [36]. Integrating remote sensing data into fire risk assessment frameworks further improves the accessibility and usability of these tools for researchers and practitioners, enabling more precise risk evaluations [35].

The strategic incorporation of risk assessment into the management cycle is organized into distinct stages: Assess and Plan, Decide and Act, and Monitor and Learn [17]. This structured approach ensures effective risk assessments are integrated into broader management strategies, allowing for continuous monitoring and adaptation based on new data and insights.

Advanced simulation frameworks, such as high-fidelity ensemble simulations, illustrate the strong interactions between environmental factors like wind speed and slope on fire spread rates, providing valuable insights that inform risk assessment and management practices [57]. Processing raster and vector data through methods involving intersection, selection, and aggregation further supports the integration of comprehensive data analysis techniques into fire risk assessments [66].

Future research should focus on enhancing the integration of diverse sensing technologies and developing advanced deep learning techniques to improve fire detection and monitoring capabilities [2]. By leveraging these advancements in technology within risk assessment frameworks, wildfire management strategies can be significantly improved, enabling more proactive and informed responses to fire hazards. This integrated approach ultimately bolsters the resilience and effectiveness of wildfire management systems in addressing the challenges posed by climate change and evolving environmental conditions.

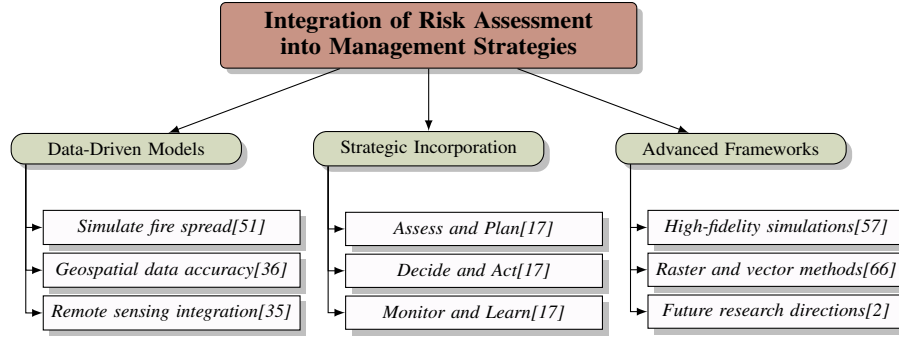


Figure 7: This figure illustrates the integration of risk assessment into wildfire management strategies, highlighting key components such as data-driven models, strategic incorporation stages, and advanced frameworks. Each component contributes to enhancing decision-making and improving resilience in fire management systems.

7 Remote Sensing Technology in Wildfire Management

7.1 Advancements in Satellite and UAV Technologies

Recent advancements in satellite and UAV technologies have significantly enhanced wildfire management through improved monitoring, detection, and data acquisition systems. The integration of advanced sensors, such as LiDAR, enables high-resolution terrain analysis essential for identifying wildfire-prone regions, as demonstrated by models estimating aboveground carbon density using ALS-derived canopy data [48]. In satellite imaging, algorithms like SatDiffMoE enhance the precision of wildfire dynamics monitoring by reconstructing high-resolution images from low-resolution captures [65], while the DFGP model improves spatiotemporal data fusion by addressing measurement errors [58].

UAV technology advancements have improved forest fire risk assessments through aerial image collection methods. UAVs equipped with dual visible and thermal cameras provide valuable datasets for analyzing fire behavior, crucial for predictive modeling and strategy refinement. The U-Net model, trained on diverse datasets, enhances burned-area detection accuracy compared to traditional methods, offering scalable mapping solutions [31]. Learning-based approaches utilizing deep learning for feature extraction have advanced data interpretation in remote sensing applications. Specialized models like SpectralGPT manage complex spectral data, enhancing scene understanding with large-scale datasets such as ChatEarthNet, which pairs satellite imagery with natural language descriptions for improved accessibility [60, 11, 67, 68, 59]. The EfficientCD model, using EfficientNet, improves change detection in fire-prone areas, facilitating timely interventions. UAV spectral sensing technologies, including point spectrometers and 2D spectral imagers, provide comprehensive spectral data critical for assessing vegetation health and fuel conditions, informing fire risk assessments.

Tools like Raster Forge, with advanced raster manipulation functions, streamline complex remote sensing data processing, making analyses more accessible. The integration of AI, ML, and 5G communication into satellite and UAV technologies underscores their transformative potential in wildfire management, enhancing monitoring and predictive capabilities while improving response strategies through real-time data collection and analysis. By employing AI-enabled remote sensing and advanced UAV sensors, fire management agencies can proactively detect wildfires, assess fuel loads, and implement effective prevention measures, ultimately protecting lives and ecosystems while mitigating economic losses associated with wildfires [20, 43].

7.2 Applications of AI and Machine Learning

AI and ML integration in processing remote sensing data has significantly enhanced wildfire monitoring and management capabilities, leveraging extensive datasets from UAVs and satellites for precise wildfire detection and risk assessment. As illustrated in Figure 8, the integration of AI and ML in remote sensing focuses on key advancements such as UAV data capture, the FLAME 3 dataset, and the U-Net model, all of which contribute to improved wildfire management. Multimodal image

registration advancements through novel algorithms and deep learning enhance image processing accuracy and efficiency [25]. The EfficientCD strategy employs a layer-by-layer decoding architecture using Euclidean distance to enhance feature representation in change detection tasks, improving environmental change and fire-prone area identification [69]. Preprocessing hyperspectral images with techniques like Gaussian transform followed by multilayer perceptron classification exemplifies sophisticated AI model feature extraction techniques for enhanced data analysis [70].

UAVs capture high-resolution spectral data, expanding remote sensing capabilities for various environmental applications, including wildfire management [26]. Advanced object detection algorithms in UAV systems enhance tree type classification, refining fire risk assessments and enabling targeted management strategies. Innovative data collection methods, such as the FLAME 3 dataset, provide high-resolution radiometric thermal TIFFs and nadir thermal plots, enriching datasets for AI and ML applications in wildfire management [71]. The U-Net model architecture effectively integrates contextual information from neighboring pixels, demonstrating improved segmentation accuracy in burned area mapping, underscoring its utility in processing remote sensing data for wildfire applications [31].

The DSS method processes AWiFS images to identify and classify water bodies and burned areas at a pixel level, utilizing distinct reflectance values to enhance classification precision [72]. These advancements illustrate AI and ML's transformative impact in remote sensing, providing enhanced tools for wildfire detection, monitoring, and management, ultimately enabling more proactive and informed responses to fire hazards.

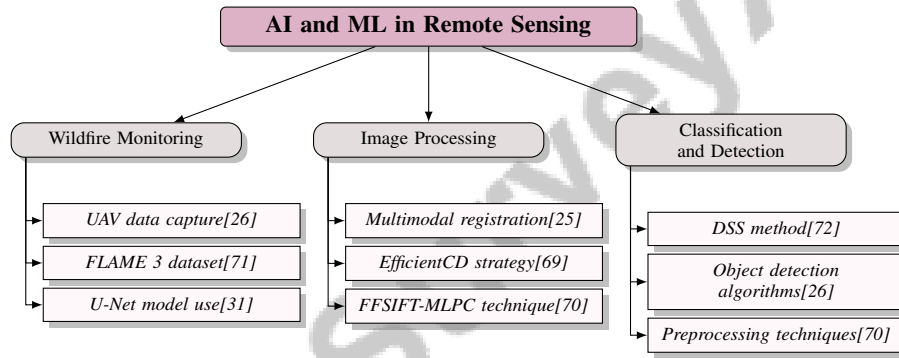


Figure 8: This figure illustrates the integration of AI and ML in remote sensing, focusing on wildfire monitoring, image processing, and classification and detection. Key advancements include UAV data capture, the FLAME 3 dataset, and the U-Net model for improved wildfire management. Image processing is enhanced through multimodal registration, EfficientCD strategy, and FFSIFT-MLPC technique. Classification and detection are advanced by the DSS method, object detection algorithms, and preprocessing techniques.

7.3 Data Integration and Processing Methods

Integrating and processing remote sensing data are critical for enhancing wildfire management systems' accuracy and efficiency. Advanced data processing techniques, such as belief-based deep reinforcement learning (DRL), optimize UAV path planning in dynamic wildfire scenarios, effectively addressing partial observability challenges and demonstrating superior performance in fire coverage and monitoring [53]. SpectralGPT exemplifies the potential of spatial-spectral coupling and sequential information to extract valuable knowledge from complex spectral data, enhancing remote sensing application understanding [67]. However, the complexity of multimodal remote sensing images, characterized by diverse scenes and noise, presents significant challenges in constructing sufficient datasets for training and testing [25].

The EfficientCD strategy enhances feature representation in change detection tasks through a layer-by-layer decoding architecture, significantly improving environmental change and fire-prone area detection [69]. Methods like FFSIFT-MLPC offer improved classification accuracy and reduced processing time compared to traditional methods, highlighting processing efficiency advancements [70]. In UAV spectral remote sensing, challenges arise from geometric and radiometric correction complexities required for accurate spectral data analysis [26]. Automating the burned-area mapping

process using Landsat imagery and time-series data exemplifies remote sensing data integration into wildfire management practices, providing scalable solutions for monitoring fire-affected regions [31].

Incorporating advanced data processing techniques into remote sensing applications has the potential to transform wildfire management. Utilizing multimodal systems like SmokeyNet, which combines camera imagery and weather sensor data for rapid smoke detection, alongside AI, ML, and 5G technology for proactive monitoring and response, enhances wildfire event monitoring, prediction, and response effectiveness. The application of multispectral aerial and satellite imagery, along with innovative datasets like FireRisk, allows for improved assessment of fire risk factors, leading to more efficient wildfire prevention and management strategies. These advancements not only enhance early detection and situational awareness but also facilitate timely interventions that can mitigate wildfires' devastating impacts on ecosystems, property, and human life [20, 35, 19, 4]. By leveraging these innovative approaches, wildfire management systems can be significantly improved, enabling more proactive and informed responses to fire hazards.

8 Ecosystem Restoration Post-Wildfire

8.1 Restoration Strategies and Implementation

Post-wildfire restoration is crucial for ecosystem recovery and resilience. Effective strategies involve a comprehensive framework of planning, execution, and monitoring, such as 'regional admixture provenancing', which enhances genetic diversity and local adaptation by mixing seeds from various populations [73]. AI and UAV technologies have transformed post-fire management, particularly in damage assessment and recovery [43]. UAVs with advanced sensors provide high-resolution data, improving the accuracy of restoration planning and monitoring [52].

Restoration processes are structured into planning, implementation, and monitoring stages, with criteria for evaluating success based on ecological and social outcomes [13]. Formal modeling techniques, like UML and Alloy, help stakeholders model and verify restoration requirements, ensuring alignment with goals [74]. Six key strategies include holistic actions, Traditional Ecological Knowledge (TEK), collaboration with allied movements, soil microbiome science, linking ecosystem and human health, and community training [75]. Integrating TEK into machine learning practices enhances community engagement, ensuring culturally relevant and ecologically sound restoration [27].

Cost-effectiveness is critical, with methods categorized as intensive (e.g., direct seeding) and less intensive (e.g., natural regeneration), the latter being more sustainable for large-scale efforts [76]. Multispectral indices demonstrate the value of advanced remote sensing in informing restoration strategies [4].

Recent studies advocate for integrating AI, Machine Learning, and 5G technologies with community engagement and TEK for effective, cost-efficient, and sustainable restoration, supporting the United Nations' Sustainable Development Goals. Collaboration among policymakers, scientists, and local communities is vital for addressing socio-cultural dimensions and ensuring long-term restoration success [27, 10, 20, 17].

8.2 Biodiversity and Ecosystem Services

Restoring biodiversity and ecosystem services post-wildfire is essential for maintaining ecological balance and human well-being. Ecosystem degradation impacts biodiversity and health, necessitating a holistic approach integrating ecological and social goals [75, 13]. Nature-based solutions reconcile wildfire management with biodiversity conservation, enhancing resilience and functionality [29]. Incorporating TEK improves community well-being and ecosystem management, highlighting the importance of involving indigenous and local communities [27].

Sourcing seeds for genetic diversity and regional adaptation is crucial. The framework by [73] enhances genetic resilience in restored ecosystems. Economic considerations are vital; intensive methods like planting are more costly than natural regeneration [76]. Formalizing ecosystem requirements using Alloy ensures reliable specifications, facilitating systematic evaluation and adjustment of restoration efforts [74].

8.3 Case Studies and Best Practices

Case studies offer insights into effective post-wildfire restoration, emphasizing the integration of scientific and local practices. Regional admixture provenancing in Germany enhances genetic diversity and adaptation through seed transfer zones [73]. The CRESTO study in Costa Rica demonstrates the benefits of formal verification in restoration, underscoring the importance of systematic evaluation and adaptive management [74]. Stakeholder engagement and adaptive management yield sustainable outcomes, highlighting the necessity of involving local communities [13].

TEK integration is a valuable asset, enhancing restoration effectiveness and equity [27]. Collaborative frameworks blending TEK with scientific methodologies improve outcomes in diverse contexts. Economic considerations are paramount; less intensive methods like natural regeneration are more cost-effective than intensive strategies [76]. Future research should explore cost-effectiveness, economies of scale, and natural regeneration's role in large-scale restoration.

9 Conclusion

The survey highlights the critical need for an integrated approach to wildfire management, emphasizing the importance of combining diverse strategies and cutting-edge technologies to address the multifaceted challenges presented by wildfires in the context of climate change. The deployment of technologies such as artificial intelligence (AI), machine learning (ML), and 5G has shown significant potential in improving wildfire detection and response, underscoring their transformative impact on management effectiveness. The advancement of AI and unmanned aerial vehicle (UAV) technologies has notably improved wildfire detection and management, showcasing the potential of autonomous systems and data analytics to enhance operational efficiency.

Infrastructure, particularly road networks, plays a pivotal role in defining potential operational delineations (PODs) and optimizing firefighting strategies. Additionally, the use of hyper-parameter optimized ML models has markedly improved predictions of fuel moisture content (FMC), demonstrating the influence of data source selection on model performance. The MRMS method has achieved notable classification accuracy in hyperspectral image analysis, highlighting the significance of selecting appropriate spectral bands.

A hierarchical framework for optimizing wildfire management has shown substantial efficiency improvements for both moderate and rapid wildfires, affirming the effectiveness of structured approaches in dynamic environments. The development of wildfire susceptibility maps for Italy has provided strong predictive capabilities, offering valuable insights for risk assessment and management strategies. The A-evac system's stochastic approach has enhanced the accuracy of evacuation safety assessments in fire scenarios, thereby improving risk evaluation and decision-making.

In policy development, constructing a forestry policy knowledge graph has effectively captured the complexities of forestry policies, surpassing existing methods in extraction accuracy. Engaging multiple stakeholders and integrating traditional knowledge with scientific methods are essential components of a comprehensive wildfire management strategy. Moreover, refining economic evaluation methodologies is crucial to inform decision-making in wildfire management.

Future research should prioritize integrating data from various social media platforms to better capture community responses and enhance understanding of public perceptions regarding wildfire threats. Further exploration into the joint estimation of adjacency matrix parameters and the incorporation of space-time structures into predictive models is also recommended. The GARST method has demonstrated a high success rate in deploying multiple UAVs, significantly reducing the total area affected by wildfires, warranting further investigation into UAV deployment strategies.

References

- [1] Kerstin Hötte and Su Jung Jee. Knowledge for a warmer world: a patent analysis of climate change adaptation technologies, 2022.
- [2] Panagiotis Barmpoutis, Periklis Papaioannou, Kosmas Dimitropoulos, and Nikos Grammalidis. A review on early forest fire detection systems using optical remote sensing. *Sensors*, 20(22):6442, 2020.
- [3] Article.
- [4] Afonso Oliveira, João P. Matos-Carvalho, Filipe Moutinho, and Nuno Fachada. Multispectral indices for wildfire management, 2025.
- [5] Matthew P Thompson, Benjamin M Gannon, and Michael D Caggiano. Forest roads and operational wildfire response planning. *Forests*, 12(2):110, 2021.
- [6] Daniela Cisneros, Jordan Richards, Ashok Dahal, Luigi Lombardo, and Raphaël Huser. Deep graphical regression for jointly moderate and extreme australian wildfires, 2024.
- [7] Martin Vejmelka, Adam K. Kochanski, and Jan Mandel. Data assimilation of dead fuel moisture observations from remote automated weather stations, 2014.
- [8] Elphin Tom Joe, Sai Dileep Koneru, and Christine J Kirchhoff. Assessing the effectiveness of gpt-4o in climate change evidence synthesis and systematic assessments: Preliminary insights, 2024.
- [9] K Mutthulakshmi, Megan Rui En Wee, Yew Chong Kester Wong, Joel Weijia Lai, Jin Ming Koh, U Rajendra Acharya, and Kang Hao Cheong. Simulating forest fire spread and fire-fighting using cellular automata. *Chinese Journal of Physics*, 65:642–650, 2020.
- [10] Purushothaman Chirakkuzhyil Abhilash. Restoring the unrestored: strategies for restoring global land during the un decade on ecosystem restoration (un-der). *Land*, 10(2):201, 2021.
- [11] Sofia Gil-Clavel and Tatiana Filatova. Using natural language processing and networks to automate structured literature reviews: An application to farmers climate change adaptation, 2024.
- [12] Ahmed Alhammadi, Anuj Abraham, Aymen Fakhreddine, Yu Tian, Jun Du, and Faouzi Bader. Envisioning the future role of 3d wireless networks in preventing and managing disasters and emergency situations, 2024.
- [13] George D Gann, Tein McDonald, Bethanie Walder, James Aronson, Cara R Nelson, Justin Jonson, James G Hallett, Cristina Eisenberg, Manuel R Guariguata, Junguo Liu, et al. International principles and standards for the practice of ecological restoration. *Restoration ecology*, 27(S1):S1–S46, 2019.
- [14] Philipp Dominic Siedler. Collaborative auto-curricula multi-agent reinforcement learning with graph neural network communication layer for open-ended wildfire-management resource distribution, 2022.
- [15] Osama M. Bushnaq, Anas Chaaban, and Tareq Y. Al-Naffouri. The role of uav-iot networks in future wildfire detection, 2020.
- [16] Harry West, Nevil Quinn, and Michael Horswell. Remote sensing for drought monitoring & impact assessment: Progress, past challenges and future opportunities. *Remote Sensing of Environment*, 232:111291, 2019.
- [17] David E Calkin, Christopher D O'Connor, Matthew P Thompson, and Richard D Stratton. Strategic wildfire response decision support and the risk management assistance program. *Forests*, 12(10):1407, 2021.
- [18] Jiazhen Liu, Peihan Li, Yuwei Wu, Gaurav S. Sukhatme, Vijay Kumar, and Lifeng Zhou. Multi-robot target tracking with sensing and communication danger zones, 2024.

-
- [19] Siddhant Baldota, Shreyas Anantha Ramaprasad, Jaspreet Kaur Bhamra, Shane Luna, Ravi Ramachandra, Eugene Zen, Harrison Kim, Daniel Crawl, Ismael Perez, Ilkay Altintas, Garrison W. Cottrell, and Mai H. Nguyen. Multimodal wildland fire smoke detection, 2022.
- [20] Stanley Chinedu Okoro, Alexander Lopez, and Austine Unuriode. A synergistic approach to wildfire prevention and management using ai, ml, and 5g technology in the united states, 2024.
- [21] Mark Beighley and AC Hyde. Portugal wildfire management in a new era assessing fire risks, resources and reforms. *Centro de Estudos Florestais-Instituto Superior de Agronomia/Universidade de Lisboa*, 2018.
- [22] Jordi Planas, Daniel Firebanks-Quevedo, Galina Naydenova, Ramansh Sharma, Cristina Taylor, Kathleen Buckingham, and Rong Fang. Beyond modeling: Nlp pipeline for efficient environmental policy analysis, 2022.
- [23] Mark A. Kramer, Allen Leavens, and Alexander Scarlet. Harnessing ai for efficient analysis of complex policy documents: a case study of executive order 14110, 2024.
- [24] Daniel Schiff, Bogdana Rakova, Aladdin Ayes, Anat Fanti, and Michael Lennon. Principles to practices for responsible ai: Closing the gap, 2020.
- [25] Bai Zhu, Liang Zhou, Simiao Pu, Jianwei Fan, and Yuanxin Ye. Advances and challenges in multimodal remote sensing image registration, 2023.
- [26] Helge Aasen, Eija Honkavaara, Arko Lucieer, and Pablo J Zarco-Tejada. Quantitative remote sensing at ultra-high resolution with uav spectroscopy: a review of sensor technology, measurement procedures, and data correction workflows. *Remote Sensing*, 10(7):1091, 2018.
- [27] Bogdana Rakova and Alexander Winter. Leveraging traditional ecological knowledge in ecosystem restoration projects utilizing machine learning, 2020.
- [28] Susete Marques, Marco Marto, Vladimir Bushenkov, Marc McDill, and JoséG Borges. Addressing wildfire risk in forest management planning with multiple criteria decision making methods. *Sustainability*, 9(2):298, 2017.
- [29] Adrián Regos, João Carlos Campos, Beatriz Albuquerque, Emilio Civantos, and João Pradinho Honrado. Land-use policies overcome fire suppression effects on functional diversity in a fire-prone, abandoned mountain area. 2022.
- [30] Sean McGregor, Rachel Houtman, Claire Montgomery, Ronald Metoyer, and Thomas G. Dietterich. Fast optimization of wildfire suppression policies with smac, 2017.
- [31] Ian Mancilla-Wulff, Jaime Carrasco, Cristobal Pais, Alejandro Miranda, and Andres Weintraub. Two scalable approaches for burned-area mapping using u-net and landsat imagery, 2023.
- [32] Asma Elmaizi, Elkebir Sarhrouni, Ahmed Hammouch, and Nacir Chafik. Hyperspectral images classification and dimensionality reduction using spectral interaction and svm classifier, 2022.
- [33] Zihui Ma, Guangxiao Hu, Ting-Syuan Lin, Lingyao Li, Songhua Hu, Loni Hagen, and Gregory B. Baecher. Assessing response disparities in california wildland-urban-interface (wui) cities using the compartmental model, 2024.
- [34] Anna Josephson, Rodrigo Guerra Su, Greg Collins, and Katharine Jacobs. The economics of climate adaptation: An assessment, 2024.
- [35] Shuchang Shen, Sachith Seneviratne, Xinye Wanyan, and Michael Kirley. Firerisk: A remote sensing dataset for fire risk assessment with benchmarks using supervised and self-supervised learning. In *2023 international conference on digital image computing: techniques and applications (DICTA)*, pages 189–196. IEEE, 2023.
- [36] Erico Kutchartt, José Ramón González-Olabarria, Núria Aquilué, Jordi Garcia-Gonzalo, Antoni Trasobares, Brigitte Botequim, Marius Hauglin, Palaiologos Palaiologou, Vassil Vassilev, Adrian Cardil, Miguel Ángel Navarrete, Christophe Orazio, and Francesco Pirotti. Pan-european fuel map server: an open-geodata portal for supporting fire risk assessment, 2024.

-
- [37] Mohammadjavad Khosravi, Rushiv Arora, Saeede Enayati, and Hossein Pishro-Nik. A search and detection autonomous drone system: from design to implementation, 2022.
- [38] Konstantinos Vogiatzoglou, Costas Papadimitriou, Vasilis Bontozoglou, and Konstantinos Ampountolas. Physics-informed neural networks for parameter learning of wildfire spreading, 2024.
- [39] Mahdi Al-Husseini, Kyle Wray, and Mykel Kochenderfer. Hierarchical framework for optimizing wildfire surveillance and suppression using human-autonomous teaming, 2024.
- [40] Chang Liu and Tamas Sziranyi. Optimal wildfire escape route planning for drones under dynamic fire and smoke, 2023.
- [41] Mohsen Naderpour, Hossein Mojaddadi Rizeei, Nima Khakzad, and Biswajeet Pradhan. Forest fire induced natech risk assessment: A survey of geospatial technologies. *Reliability Engineering & System Safety*, 191:106558, 2019.
- [42] Josy John and Suresh Sundaram. Genetic algorithm-based routing and scheduling for wildfire suppression using a team of uavs, 2024.
- [43] Sayed Pedram Haeri Boroujeni, Abolfazl Razi, Sahand Khoshdel, Fatemeh Afghah, Janice L. Coen, Leo O'Neill, Peter Z. Fule, Adam Watts, Nick-Marios T. Kokolakis, and Kyriakos G. Vamvoudakis. A comprehensive survey of research towards ai-enabled unmanned aerial systems in pre-, active-, and post-wildfire management, 2024.
- [44] Soukayna Mouatadid, Paulo Orenstein, Genevieve Flaspohler, Judah Cohen, Miruna Oprescu, Ernest Fraenkel, and Lester Mackey. Adaptive bias correction for improved subseasonal forecasting, 2023.
- [45] Rasmus E. Benestad. A norwegian approach to downscaling, 2024.
- [46] Qidong Yang, Jonathan Giezendanner, Daniel Salles Civitarese, Johannes Jakubik, Eric Schmitt, Anirban Chandra, Jeremy Vila, Detlef Hohl, Chris Hill, Campbell Watson, and Sherrie Wang. Multi-modal graph neural networks for localized off-grid weather forecasting, 2024.
- [47] Adam Krasuski and Karol Krenski. A-evac: the evacuation simulator for stochastic environment, 2017.
- [48] Tommaso Jucker, Gregory P. Asner, Michele Dalponte, Philip Brodrick, Christopher D. Philipson, Nick Vaughn, Craig Brelsford, David F. R. P. Burslem, Nicholas J. Deere, Robert M. Ewers, Jakub Kvasnica, Simon L. Lewis, Yadvinder Malhi, Sol Milne, Reuben Nilus, Marion Pfeifer, Oliver Phillips, Lan Qie, Nathan Renneboog, Glen Reynolds, Terhi Riutta, Matthew J. Struebig, Martin Svátek, Yit Arn Teh, Edgar C. Turner, and David A. Coomes. A regional model for estimating the aboveground carbon density of borneo's tropical forests from airborne laser scanning, 2017.
- [49] Philip A. White, Michael F. Christensen, Henry Frye, Alan E. Gelfand, and John A. Silander Jr au2. Joint multivariate and functional modeling for plant traits and reflectances, 2022.
- [50] Dayou Chen, Sibao Cheng, Jinwei Hu, Matthew Kasoar, and Rossella Arcucci. Explainable global wildfire prediction models using graph neural networks, 2024.
- [51] Tina Diao, Samridhi Singla, Ayan Mukhopadhyay, Ahmed Eldawy, Ross Shachter, and Mykel Kochenderfer. Uncertainty aware wildfire management, 2020.
- [52] Harnaik Dharmi. Planning and perception for unmanned aerial vehicles in object and environmental monitoring, 2024.
- [53] Sahand Khoshdel, Qi Luo, and Fatemeh Afghah. Pyrotrack: Belief-based deep reinforcement learning path planning for aerial wildfire monitoring in partially observable environments, 2024.
- [54] Declan Curran, Hira Saleem, Sanaa Hobeichi, and Flora Salim. Resolution-agnostic transformer-based climate downscaling, 2024.
- [55] J. Prpic, A. Taeihagh, and J. Melton. Experiments on crowdsourcing policy assessment, 2017.

-
- [56] Jingyun Sun and Zhongze Luo. Forpkg-1.0: A framework for constructing forestry policy knowledge graph and application analysis, 2024.
- [57] Qing Wang, Matthias Ihme, Cenk Gazen, Yi-Fan Chen, and John Anderson. Firebench: A high-fidelity ensemble simulation framework for exploring wildfire behavior and data-driven modeling, 2024.
- [58] Pulong Ma and Emily L. Kang. Spatio-temporal data fusion for massive sea surface temperature data from modis and amsr-e instruments, 2019.
- [59] Li Chen, Guowei Zhu, Qi Li, and Haifeng Li. Adversarial example in remote sensing image recognition, 2020.
- [60] Zhenghang Yuan, Zhitong Xiong, Lichao Mou, and Xiao Xiang Zhu. Chatearthnet: A global-scale image-text dataset empowering vision-language geo-foundation models, 2024.
- [61] Sean McGregor, Rachel Houtman, Claire Montgomery, Ronald Metoyer, and Thomas G. Dietterich. Factoring exogenous state for model-free monte carlo, 2017.
- [62] Josy John, Shridhar Velhal, and Suresh Sundaram. A resource-efficient decentralized sequential planner for spatiotemporal wildfire mitigation, 2024.
- [63] John S. Schreck, William Petzke, Pedro A. Jimenez, Thomas Brummet, Jason C. Knievel, Eric James, Branko Kosovic, and David John Gagne. Machine learning and viirs satellite retrievals for skillful fuel moisture content monitoring in wildfire management, 2023.
- [64] Zhihui Tian, John Upchurch, G. Austin Simon, José Dubeux, Alina Zare, Chang Zhao, and Joel B. Harley. Quantifying heterogeneous ecosystem services with multi-label soft classification, 2024.
- [65] Zhaoxu Luo, Bowen Song, and Liyue Shen. Satdiffmoe: A mixture of estimation method for satellite image super-resolution with latent diffusion models, 2024.
- [66] Samridhi Singla and Ahmed Eldawy. Raptor zonal statistics: Fully distributed zonal statistics of big raster + vector data [pre-print], 2020.
- [67] Danfeng Hong, Bing Zhang, Xuyang Li, Yuxuan Li, Chenyu Li, Jing Yao, Naoto Yokoya, Hao Li, Pedram Ghamisi, Xiuping Jia, et al. Spectralgpt: Spectral remote sensing foundation model. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 2024.
- [68] Bo Du, Lixiang Ru, Chen Wu, and Liangpei Zhang. Unsupervised deep slow feature analysis for change detection in multi-temporal remote sensing images, 2019.
- [69] Sijun Dong, Yuwei Zhu, Geng Chen, and Xiaoliang Meng. Efficientcd: A new strategy for change detection based with bi-temporal layers exchanged, 2024.
- [70] G. Kalaiarasi and S. Maheswari. Frost filtered scale-invariant feature extraction and multilayer perceptron for hyperspectral image classification, 2020.
- [71] Bryce Hopkins, Leo O'Neill, Michael Marinaccio, Eric Rowell, Russell Parsons, Sarah Flanary, Irtija Nazim, Carl Seielstad, and Fatemeh Afghah. Flame 3 dataset: Unleashing the power of radiometric thermal uav imagery for wildfire management, 2024.
- [72] Suraj Kothawade, Kunjan Mhaske, Sahil Sharma, and Furkhan Shaikh. Content based image retrieval from awifs images repository of irs resourcesat-2 satellite based on water bodies and burnt areas, 2018.
- [73] Anna Bucharova, Oliver Bossdorf, Norbert Hölzel, Johannes Kollmann, Rüdiger Prasse, and Walter Durka. Mix and match: regional admixture provenancing strikes a balance among different seed-sourcing strategies for ecological restoration. *Conservation Genetics*, 20(1):7–17, 2019.
- [74] Tiago Sousa, Benoît Ries, and Nicolas Guelfi. Formal verification of ecosystem restoration requirements using uml and alloy, 2024.

-
- [75] James Aronson, Neva Goodwin, Laura Orlando, Cristina Eisenberg, and Adam T Cross. A world of possibilities: six restoration strategies to support the united nation's decade on ecosystem restoration. *Restoration Ecology*, 28(4):730–736, 2020.
- [76] Pedro HS Brancalion, Paula Meli, Julio RC Tymus, Felipe EB Lenti, Rubens M Benini, Ana Paula M Silva, Ingo Isernhagen, and Karen D Holl. What makes ecosystem restoration expensive? a systematic cost assessment of projects in brazil. *Biological Conservation*, 240:108274, 2019.

www.SurveyX.cn

Disclaimer:

SurveyX is an AI-powered system designed to automate the generation of surveys. While it aims to produce high-quality, coherent, and comprehensive surveys with accurate citations, the final output is derived from the AI's synthesis of pre-processed materials, which may contain limitations or inaccuracies. As such, the generated content should not be used for academic publication or formal submissions and must be independently reviewed and verified. The developers of SurveyX do not assume responsibility for any errors or consequences arising from the use of the generated surveys.

www.SurveyX.cn