Chapter 6
Actionable Science for Wildfire

Ziheng Sun

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Z. Sun (ed.), *Actionable Science of Global Environment Change*,
https://doi.org/10.1007/978-3-031-41758-0_6

1 Introduction

Wildfires pose significant dangers and have wide-ranging impacts on human life, public safety, and economy. The destruction of forests, residential areas, and infrastructure leads to the serious loss of property and assets (Fearnside 2005). It affects industries such as agriculture, forestry, tourism, and recreation. Smoke pollution can also affect air quality, leading to economic losses in sectors like transportation and tourism (Fig. 6.1). Firefighting efforts and post-fire rehabilitation entail substantial costs for governments and communities (Schumann et al. 2020). The 2018 Camp Fire in California resulted in 85 fatalities and an estimated $16.5 billion in direct economic losses (Iglesias et al. 2022), including the destruction of thousands of homes, businesses, and infrastructure. Direct exposure to flames, heat, and smoke can lead to injuries and fatalities. The inhalation of smoke particles and pollutants can cause respiratory problems and exacerbate preexisting health conditions (Ling and van Eeden 2009). Evacuations and displacement of communities further impact people's well-being and mental health. For example, the 2020 Australian bushfires resulted in the loss of over 30 human lives, widespread injuries, and the displacement of thousands of residents (Filkov et al. 2020). Wildfires can destroy natural habitats, leading to the loss of biodiversity. The combustion of vegetation releases large amounts of carbon dioxide into the atmosphere, contributing to climate change. The loss of vegetation also increases the risk of soil erosion and impacts water quality. The 2019 Amazon rainforest fires caused significant damage to one of the world's most important ecosystems (Arruda et al. 2019), leading to habitat loss

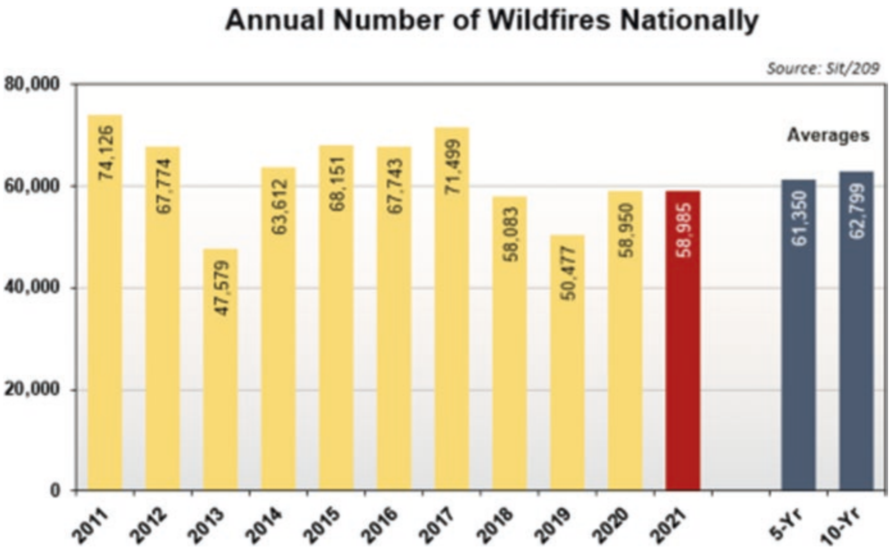


Fig. 6.1 Wildfire trends in the United States. (Image courtesy: https://www.earthdata.nasa.gov/resource-spotlight/wildfires)

for numerous plant and animal species. Wildfires can also damage critical infrastructure and utility systems, such as power lines, communication networks, and water supply facilities (Jahn et al. 2022). Disruptions in these services can have far-reaching consequences, affecting daily life, emergency response capabilities, and the functionality of essential services, such as the 2017 Thomas Fire in California destroying power lines, and resulting in power outages for thousands of residents and impacting communication systems (Kolden and Henson 2019).

Science helps us comprehend the complex behavior of wildfires, including how they ignite, spread, and interact with the environment. This knowledge is essential for developing strategies to predict fire behavior and make informed decisions regarding firefighting tactics, resource allocation, and evacuation measures. Science-based meteorological models and weather monitoring systems also help forecast fire weather conditions, such as high temperatures, low humidity, and strong winds (Rummukainen 2012). Accurate predictions enable early warning systems and provide critical information to fire management agencies, allowing them to prepare and allocate resources effectively (Grasso and Singh 2011). Understanding the ecological role of fire in different ecosystems aids in developing strategies for prescribed burning and ecosystem management. Science-based research contributes to identifying fire-adaptive species, managing invasive plants, and restoring fire-dependent ecosystems (Dennis-Parks 2004). It helps strike a balance between suppressing wildfires for public safety and allowing natural fire regimes to maintain ecosystem health (Moritz et al. 2014). Science also allows for the assessment of fire risk by considering various factors such as vegetation type, fuel moisture content, topography, and historical fire data (Yebra et al. 2013). The findings of scientists can aid in post-fire assessments to evaluate the impact on ecosystems, water quality, and soil erosion and develop strategies for post-fire rehabilitation and restoration of affected areas, including reforestation efforts, erosion control measures, and habitat restoration (Bento-Gonçalves et al. 2012). However, all these need to rely on the collaboration between continued scientific research and fire management agencies and communities to advance our knowledge and improve wildfire control strategies.

Without actionable science, the communities will face increased risks and vulnerabilities, leading to significant negative impacts on their lives. Nonactionable research will result in inadequate understanding of fire behavior and ineffective evacuation planning, which can lead to delays or failures in issuing timely evacuation orders. For example, in the 2018 Camp Fire in California, the lack of actionable research for the power grid companies like PG&E and poor evacuation planning contributed to the loss of 85 lives (Conway 2021). Actionable science can greatly help in developing evidence-based evacuation plans, identifying evacuation zones, determining evacuation timelines, and improving public communication during wildfire events (Seeger et al. 2018). It can enable the identification of high-risk areas and helps prioritize resource allocation for prevention measures, such as fuel management, prescribed burns, and public education campaigns.

However, a lot of wildfire research is not practical for real-world application. They often involve complex scientific models, laboratory experiments, or simulations that may not directly translate into operational strategies for fire management agencies (Sayad et al. 2019). The challenge lies in bridging this gap and effectively communicating research findings to practitioners in a format that is applicable and useful (Enquist et al. 2017). In addition, conducting research takes time, and the timeline for scientific studies may not align with the urgent needs of wildfire management. The dynamic and rapidly evolving nature of wildfires requires immediate decision-making and response, which may not allow for the integration of recent scientific findings into operational practices. On the other hand, wildfires present numerous practical challenges, such as unpredictable weather conditions, rugged terrain, limited resources, and the need for quick decision-making. These constraints can make it challenging to implement certain research findings that require extensive resources, specialized equipment, or ideal conditions that may not be feasible during a wildfire event. Also, the struggle of science to be realistic is always there as wildfire behavior is influenced by a multitude of factors, including weather, topography, fuel conditions, and human factors (Christianson 2014). The complexity and uncertainty associated with wildfire dynamics make it difficult to develop universally applicable and actionable research findings that can be applied across diverse landscapes and fire situations.

This chapter will first examine the current practice in wildfire prevention, responding, and recovery, and find the success and failures of application of scientific results, like the use of fire weather forecasts, fuel management strategies based on ecological research, and the development of fire behavior models that aid in fire suppression efforts (Finney and Cohen 1998). The failures will involve situations where scientific knowledge was not effectively integrated into operational practices, resulting in inadequate fire suppression strategies, evacuation planning, or post-fire recovery efforts. These examples demonstrate how actionable scientific findings have contributed to effective wildfire prevention and response. It will touch on issues like the research-practice gap, time constraints, practical limitations, complexity and uncertainty in wildfire dynamics, and policy or institutional barriers. Eventually give out a list of suggestions for scientists and stakeholders to go forward to work together and improve the actionableness of wildfire research. Emphasizing the importance of conducting applied research in real-world settings can enhance the practicality and relevance of wildfire scientific findings. This could involve conducting experiments, field studies, and simulations that mimic operational conditions and directly address the challenges faced during wildfire prevention, response, and recovery.

2 Current Practice in Wildfire Management

Effective wildfire management requires a comprehensive understanding of the current practices employed. This section looks into the existing approaches and strategies employed by fire management agencies, aiming to evaluate their success and failures in applying scientific research to wildfire management. By examining real-world examples, both successful and failed ones, we can gain insights into the practical application of scientific findings and identify areas for improvement (Thompson et al. 2019). From the utilization of fire weather forecasts to fuel management strategies and fire behavior modeling, this section provides an overview of the current state of wildfire management and sets the foundation for understanding the challenges and opportunities in enhancing the actionableness of wildfire research.

2.1 Emergency Response and Firefighting Tactics

Here we overview the current responding code from initial detection and rapid mobilization to on-the-ground firefighting techniques, such as fire suppression, containment, and perimeter control. The initial step is the timely detection and reporting of wildfires. This can be achieved through various methods, such as lookout towers, aerial surveillance, remote sensing technologies, and public reports. For instance, advanced satellite systems like NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) can detect active fire hotspots, alerting authorities to the presence of wildfires (Giglio et al. 2006). In addition, community members who spot smoke or flames can report them to local fire departments, initiating the emergency response process.

Once a wildfire is reported, incident management teams assess the situation by gathering critical information about the fire's location, size, behavior, and potential threats. This assessment guides the development of an incident action plan, including objectives, strategies, and tactics for managing the fire. For example, fire behavior analysts analyze factors such as fuel conditions, weather patterns, and topography to understand how the fire might spread and develop appropriate response strategies.

With the incident action plan in place, firefighting resources are mobilized to the affected area. This includes firefighters, fire engines, bulldozers, aircraft, and support personnel. For instance, during the devastating 2020 wildfires in California (Keeley and Syphard 2021), resources from local, state, and federal agencies were deployed, including CAL FIRE crews, National Guard units, and specialized firefighting aircraft like air tankers and helicopters (Gagnon 2021). Firefighters employ various tactics to suppress and contain the fire. These tactics involve both direct and indirect approaches. In a direct attack, firefighters engage the fire head-on using hand tools, hoses, and fire retardants. In contrast, indirect attack tactics focus on creating control lines to halt the fire's advance. This can involve constructing firebreaks, removing vegetation, and conducting tactical firing operations to remove fuel. During the Australian bushfire crisis in 2019–2020, firefighters used these tactics to combat the rapidly spreading fires (Ward et al. 2020).

Perimeter control is vital to prevent the fire from spreading beyond predetermined boundaries (Tymstra et al. 2010). Firefighters work to establish and reinforce control lines around the fire's perimeter. This can include clearing vegetation, creating wider firebreaks, and implementing strategic backburning operations. These actions aim to limit the fire's spread and protect communities and valuable assets.

For instance, during the 2021 Oregon Bootleg Fire (Marsavin et al. 2023), firefighters used bulldozers and hand crews to construct control lines and protect nearby communities.

Once the fire is contained, mop-up operations begin. Firefighters carefully extinguish hotspots and smoldering embers along the fire's edge to prevent reignition. Rehabilitation efforts focus on restoring the impacted area by rehabilitating damaged ecosystems, stabilizing soil, and implementing erosion control measures. This ensures that the fire is fully extinguished and minimizes long-term environmental impacts. For instance, after the devastating wildfires in Australia, rehabilitation efforts involved reseeding burnt areas, restoring habitats, and supporting the recovery of affected wildlife.

Throughout the entire firefighting, incident command structures, such as the Incident Command System (ICS) (Chang 2017), facilitate coordination, communication, and decision-making among firefighting agencies, emergency management personnel, and other stakeholders. These structures provide a unified framework for managing the incident and ensure efficient resource allocation and strategic planning. It is important to acknowledge that the effectiveness of emergency response and firefighting tactics depends on various factors, including fire behavior, weather conditions, terrain, available resources, and community preparedness.

2.2 Wildfire Prevention and Preparedness

Wildfire prevention and preparedness usually involves assessing factors such as fuel load, vegetation type, weather patterns, and proximity to communities and critical infrastructure (Tymstra et al. 2020). Based on the assessment, wildfire risk zones can be identified, guiding the development of prevention and preparedness strategies. For instance, in high-risk areas, regulations may be implemented to restrict activities that could spark wildfires, such as campfire bans or restrictions on outdoor burning (Barlow and Carlos 2004). Fuel management plays a crucial role in reducing the availability and continuity of combustible materials, including fuel reduction techniques like prescribed burning, mechanical clearing, and vegetation management around structures. Prescribed burning involves controlled fires set under specific conditions to remove accumulated fuels and promote healthier ecosystems (Prichard et al. 2021). Mechanical clearing may involve the use of equipment like mowers, chippers, and chainsaws to create firebreaks and reduce fuel loads. These measures aim to create defensible space and limit the potential for wildfires to spread rapidly.

Deploying early warning systems is comprised of the installation of wildfire detection technologies like cameras, satellite monitoring, and automated weather stations. These systems provide real-time information on fire activity, enabling prompt response and evacuation when necessary. For instance, in Australia, the Victorian Bushfire Information Line and the Country Fire Authority (CFA) use a combination of technologies to monitor fire behavior and issue warnings to affected communities (Teague et al. 2010). A good example system is the Canada Wildland Fire Information System (CWFIS) (Anderson 2005), which is an online platform that provides comprehensive information on wildfires in Canada (Fig. 6.2). It is a collaborative effort between federal, provincial, and territorial fire management agencies to enhance fire management, public safety, and awareness. The system offers various tools and resources for monitoring and reporting wildfires across the country. The FWI System is a key component of CWFIS and assesses the potential behavior of wildfires based on weather conditions. It includes several indices, such as the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Buildup Index (BUI), which help assess fire danger and predict fire behavior. The system provides daily reports on fire weather conditions, fire behavior predictions, and fire danger ratings. These reports help fire management agencies and other stakeholders make informed decisions regarding fire suppression, resource allocation, and public safety. The CWFIS features an interactive fire danger map that displays real-time fire danger ratings across Canada. This map helps users visualize areas of high fire risk and assists in allocating firefighting resources and implementing fire restrictions. The system offers real-time active fire mapping, which provides the location, extent, and intensity of ongoing wildfires across the country. This information is crucial for situational awareness, incident response, and public safety. It has fire perimeter mapping, which provides the boundary of the burned areas for large

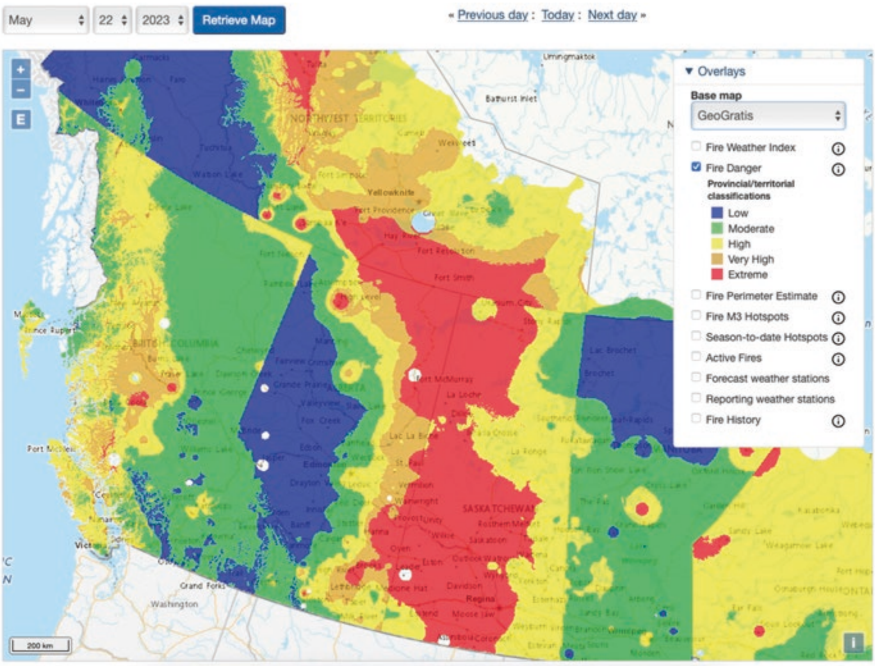


Fig. 6.2 Canada Wildland Fire Information System (CWFIS) fire danger map interface

wildfires. This mapping helps assess the impact of fires, monitor fire progression, and support post-fire analysis and recovery efforts.

Wildfire prevention and preparedness involve fostering collaboration and resource sharing among firefighting agencies and neighboring communities. Mutual aid agreements and partnerships enable the sharing of personnel, equipment, and resources during wildfire incidents. This cooperative approach ensures a coordinated response and enhances the capacity to address large-scale wildfires. An example of mutual aid is the Pacific Northwest Wildfire Compact in the United States, where states collaborate to provide assistance during wildfire emergencies.

Developing robust emergency plans and evacuation procedures is crucial for protecting lives and property. This involves working closely with emergency management agencies, local governments, and communities to establish evacuation routes, assembly points, and communication protocols. Public awareness campaigns and drills help prepare residents to respond effectively during evacuation orders. For instance, during the 2018 Tubbs Fire in California, coordinated evacuation efforts saved lives and facilitated efficient movement of residents to safe locations (Kramer et al. 2019).

2.3 Community Preparedness and Education

Importance of Community Engagement and Involvement

Engaging communities in wildfire prevention and preparedness efforts ensures that residents understand the risks, are equipped with necessary knowledge, and actively participate in mitigation strategies. Recent examples highlight the significance of community involvement. For instance, in the aftermath of the devastating 2019–2020 Australian bushfires, affected communities actively engaged in recovery initiatives, including tree planting, habitat restoration, and community-led fire preparedness workshops. In the United States, community-based organizations like Fire Safe Councils have been instrumental in promoting fire-adaptive communities by organizing educational programs, community clean-up events, and fuel reduction projects (Everett and Fuller 2011). These examples demonstrate how community engagement strengthens resilience, fosters collective responsibility, and enhances the overall effectiveness of wildfire management efforts.

Education and Outreach Programs on Wildfire Prevention and Response

Educating the public about wildfire risks and promoting preparedness is vital as well. Public education campaigns raise awareness about safe practices, such as proper disposal of cigarette butts, the use of fire-resistant materials in construction, and creating defensible space around homes (Weber et al. 2019). Community workshops, informational materials, and interactive websites can provide valuable resources for individuals to understand and mitigate wildfire risks. For example, in fire-prone regions like California, organizations like CAL FIRE conduct outreach programs to educate residents on wildfire prevention and preparedness measures.

Collaborative Approaches Between Scientists, Communities, and Agencies

Collaboration across various parties is essential for leveraging diverse expertise, local knowledge, and shared resources. Real-world examples highlight the success of such collaborations. In California, the UC Berkeley Fire Center partnered with local communities and fire agencies to develop the Firewise Communities program, which engages residents in creating defensible spaces around their properties and implementing fire-resistant landscaping. This collaborative effort has resulted in increased community preparedness and reduced wildfire risk (Smith et al. 2016). Similarly, in Australia, the Bushfire and Natural Hazards Cooperative Research Centre (Sharples et al. 2016) works closely with firefighters, emergency services, and local communities to co-produce research and develop practical solutions. This collaboration has led to improved fire behavior predictions, enhanced early warning systems, and community-led initiatives like the Fireballs in the Sky citizen science project. These examples demonstrate how collaborative approaches foster innovation, build trust, and enhance the resilience of communities in the face of wildfires.

2.4 Post-Fire Recovery and Resilience

This section focuses on the phases following wildfires, where communities and ecosystems work toward recovery and building resilience. We examine the key factors that contribute to successful post-fire recovery, including ecological restoration, community support, and long-term planning. The section emphasizes the importance of integrating science-based approaches into recovery efforts, such as assessing soil health, replanting native vegetation, and implementing erosion control measures. Additionally, it highlights the significance of engaging local communities in decision-making processes to ensure their needs and perspectives are considered. By adopting a holistic and collaborative approach, post-fire recovery and resilience efforts can mitigate the long-lasting impacts of wildfires and foster the restoration of both natural and human systems.

Assessment of Post-Fire Impacts on Ecosystems and Communities

Immediately after a wildfire, emergency response teams conduct an initial assessment to determine the safety of the affected area and identify any immediate threats to households. Once it is safe to enter the impacted area, damage assessment teams, including experts from various fields, conduct detailed surveys to evaluate the extent of damage to individual households. This includes assessing structural damage, loss of personal belongings, and potential hazards such as fallen trees or unstable structures. Concurrently, teams work closely with impacted households to understand their immediate and long-term needs. This involves conducting interviews and surveys to assess the requirements for temporary shelter, food, water, medical assistance, and other essential services. Ecologists and environmental scientists evaluate the impacts of the wildfire on the surrounding ecosystems. This includes studying the loss of vegetation, changes in soil quality, and potential threats to wildlife habitats. Field surveys, remote sensing techniques, and data analysis help in assessing the ecological impacts. Social scientists and community organizations collaborate to assess the social and psychological impacts on affected households. This involves understanding the emotional trauma, displacement, and community disruptions caused by the fire. Surveys, interviews, and focus groups are conducted to gather information and provide support to those affected. The collected data from the assessments are analyzed to generate comprehensive reports. These reports highlight the findings, including the extent of damage, immediate needs of households, and the ecological and social impacts. The reports are crucial in informing policymakers, agencies, and organizations involved in the recovery and rebuilding process.

Real wildfire examples, such as the 2018 California Camp Fire, illustrate how this assessment process plays out. Teams on the ground assessed the damage to individual households, identified immediate needs like shelter and medical assistance, evaluated the ecological impacts on nearby forests and wildlife habitats, and worked closely with communities to understand the social and psychological impacts (Knapp et al. 2021). The gathered information helped in providing targeted support and guiding the recovery efforts to ensure the resilience and well-being of the affected households.

Restoration and Rehabilitation Strategies for the Affected Areas

The post-fire assessment helps in understanding the specific needs and challenges of the affected areas. Based on the assessment, a restoration plan is developed. This plan outlines the goals, objectives, and strategies for restoring the natural ecosystem (Steelman and Burke 2007). It includes actions such as reseeding native plants, implementing erosion control measures, and enhancing wildlife habitats. The plan also considers the resilience and adaptability of the ecosystem in the face of future fire events. Restoring vegetation is a critical aspect of the rehabilitation process. This involves planting native species, including trees, shrubs, and grasses, to stabilize the soil, prevent erosion, and provide habitat for wildlife. Seed collection, nursery propagation, and strategic planting techniques are utilized to ensure successful establishment. Burned areas are prone to erosion, which can further degrade the ecosystem. Soil stabilization techniques, such as mulching, terracing, and erosion control blankets, are implemented to reduce erosion risks and promote soil health (Ahmad et al. 2020). These measures help prevent sedimentation in nearby water bodies and support the recovery of native plant species. Also, efforts are made to restore and enhance wildlife habitats in the fire-affected areas, including creating nesting sites, installing bird boxes, and constructing structures like snag trees to provide shelter and breeding areas for wildlife, which aims to support the recovery of diverse species and promote ecological balance. Throughout the restoration process, ongoing monitoring is conducted to assess the success of implemented strategies and make necessary adjustments. Monitoring includes tracking vegetation regrowth, evaluating soil stability, and assessing wildlife presence. Adaptive management allows for modifications to the restoration plan based on scientific observations and emerging knowledge. Meanwhile, restoration efforts often involve active engagement with local communities, landowners, and stakeholders. This collaboration promotes a sense of ownership and encourages community participation in the restoration process such as volunteer programs, educational initiatives, and partnerships with community organizations to foster long-term stewardship of the restored areas.

Long-Term Planning for Wildfire Resilience

Effective long-term planning requires appropriate land use practices and zoning regulations to reduce wildfire vulnerability such as limiting development in high-risk areas, implementing setbacks and defensible space requirements around structures, and encouraging fire-resistant building materials and designs (Schumann et al. 2020). Zoning ordinances and building codes are updated and enforced to ensure adherence to wildfire resilience guidelines. To reduce the risk of wildfire ignition and spread, the planning needs to emphasize fuel management strategies like implementing controlled burns, mechanical treatments, and vegetation thinning programs to reduce the accumulation of flammable materials, such as dead trees, shrubs, and brush. Strategic fuel breaks are created to interrupt the path of wildfires and provide opportunities for firefighting operations. Critical infrastructure, including power lines, transportation networks, and communication systems, are assessed and modified to enhance their resilience to wildfires. Planning also addresses water availability and accessibility for firefighting purposes. In addition, planning incorporates the establishment and enhancement of early warning systems to provide timely information and alerts to communities and deploy weather monitoring stations, remote sensing technologies, and community notification systems. Monitoring includes tracking changes in fuel loads, evaluating the success of fuel management projects, and assessing the resilience of ecosystems. This information helps guide adaptive management approaches to continuously improve wildfire resilience strategies. Other emergency preparedness efforts like evacuation planning, community drills, and the development of evacuation routes and shelters will also be included. The planning should recognize the dynamic nature of wildfires and the need for ongoing assessment and adaptation. Regular evaluations of planning strategies and practices are conducted to identify successes, challenges, and areas for improvement. This iterative process also allows for the integration of new scientific findings to improve the planning.

2.5 Challenges and Limitations of Current Practice

Climate change has contributed to longer and more intense wildfire seasons, making it challenging to manage wildfires effectively (Hessburg et al. 2021). The increased frequency of wildfires puts a strain on resources and makes it difficult to allocate them appropriately. Limited resources can lead to delays in response time, inadequate suppression efforts, and difficulty in implementing prevention and mitigation measures. Many communities in wildfire-prone areas are located in the wildland–urban interface, where homes and structures intermingle with natural vegetation. This poses a significant challenge as it increases the risk to both human lives and property during wildfire events. Challenges such as limited evacuation routes, lack of preparedness among residents, and inadequate communication systems can impede evacuation efforts and put lives at risk. There are also limitations to conducting prescribed burns, including air quality concerns, regulatory barriers, and public acceptance issues. Meanwhile, invasive species and forest health issues can exacerbate wildfire risks. The spread of invasive plants and pests can increase fuel loads and make ecosystems more susceptible to fire. Managing these factors requires long-term strategies and collaboration between various stakeholders. Many individuals residing in wildfire-prone areas lack awareness and understanding of wildfire risks, prevention measures, and evacuation procedures. Insufficient education and outreach efforts can hinder effective preparedness and response during wildfire events (Keim 2008). Besides, fragmented communication systems, jurisdictional challenges, and differing priorities can impede seamless cooperation and hinder response efforts. Liability concerns and legal complexities associated with wildfire management can impact prescribed burning, land management decisions, and insurance coverage, making it challenging to implement effective strategies. Activities like assessing post-fire impacts, securing funding for restoration efforts, and addressing social and economic impacts on affected communities are always complex and resource-intensive processes.

2.6 Shift Toward a More Proactive and Science-Based Approach

Advanced technologies and monitoring systems can improve early detection and warning capabilities. This includes the use of satellite imagery, remote sensing, and weather monitoring tools to detect and predict fire behavior accurately (Yuan et al. 2015). Timely and reliable information allows for proactive decision-making and efficient resource allocation. By integrating scientific data and community input, decision-makers can develop targeted strategies for fuel management, land use planning, and infrastructure protection. Implementing proactive fuel management practices, including prescribed burning, can reduce fuel loads and create defensible spaces around communities. By strategically conducting controlled burns during favorable conditions, the risk of uncontrolled wildfires can be minimized. Collaboration with stakeholders, including landowners, agencies, and communities, is essential to address concerns, increase acceptance, and expand prescribed burning efforts. Continual investment in research and innovation is vital for advancing wildfire management practices. This includes studying fire behavior, climate change impacts, ecosystem resilience, and technological advancements. By integrating the latest scientific findings into management strategies, decision-makers can adapt and improve their approaches over time. Updating policies and governance frameworks to align with a proactive and science-based approach is crucial. This involves incentivizing and supporting proactive measures, such as prescribed burning and fuel management, through regulatory reforms, funding mechanisms, and insurance incentives. It also requires integrating climate change considerations and long-term planning into land and resource management policies. However, adequate and sustained funding is essential to support research, infrastructure development, community programs, and firefighting resources. Securing long-term funding commitments from government agencies and exploring innovative funding models can ensure the continuity of proactive wildfire management efforts.

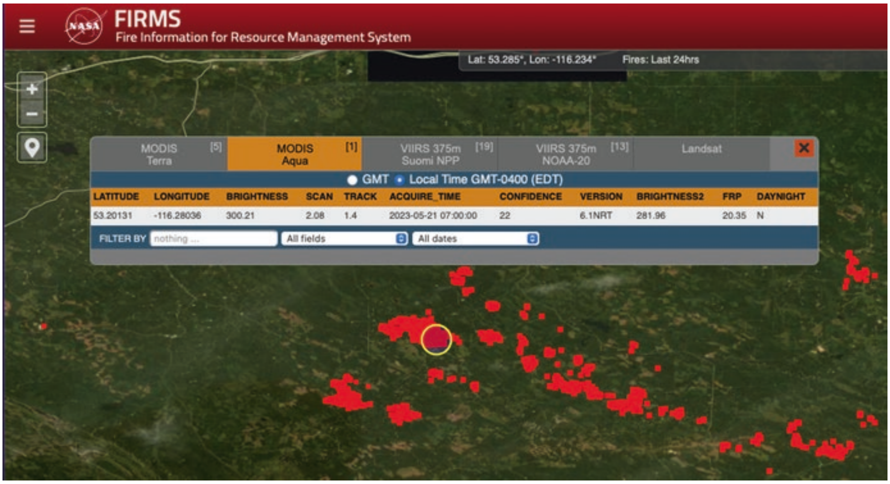
3 Advanced Research for Wildfire

Through innovative technologies, such as satellite imagery, remote sensing, and computer modeling, scientists can accurately monitor fire behavior, predict fire spread, and assess fire risk. Recent research efforts focus on studying the impacts of climate change on wildfire frequency and severity, exploring new firefighting techniques, and developing proactive strategies for prevention and mitigation. This section will introduce some cutting-edge topics in this type of research.

3.1 Remote Sensing Research for Early Detection and Monitoring

Barmpoutis et al. (2020a) provide an overview of optical remote sensing technologies used in early fire warning systems, focusing on flame and smoke detection algorithms. It categorizes the systems into terrestrial, airborne, and spaceborne-based, and discusses the strengths and weaknesses of optical remote sensing for fire detection. The findings aim to contribute to future research projects and the development of improved early warning fire systems. Xu and Xu (2017) explore the use of the geostationary Himawari-8 satellite to generate real-time information about ongoing wildfires in Australia. The satellite's high-temporal-resolution multispectral imagery allows for large-scale monitoring and detection of wildfires. The case study of the 2015 Esperance wildfire demonstrates the satellite's effectiveness in detecting wildfires, even in the presence of smoke and moderate cloud cover. It also enables the real-time monitoring of fire spread rates and directions, offering potential for automated detection of abnormal fire behavior. Yuan et al. (2017) present a novel forest fire detection method using unmanned aerial vehicles (UAVs) equipped with vision-based systems. The method combines color and motion features to identify fire candidate regions in images captured by the UAV's camera. A color-based fire detection algorithm extracts fire-colored pixels, while two types of optical flow algorithms compute motion vectors of the fire candidate regions. Experimental results demonstrate the effectiveness of the proposed method in accurately extracting and tracking fire pixels in aerial video sequences, improving forest fire detection accuracy while minimizing false alarms. Hua and Shao (2017) provide an overview of forest fire monitoring (FFM) using satellite- and drone-mounted infrared remote sensing (IRRS). The review encompasses different IRRS algorithms, with a focus on spatial contextual methods that can be applied using commonly available satellite data. Medium-resolution IRRS data and specific algorithms are identified as effective tools for landscape-scale monitoring and early warning of forest fires. Sherstjuk et al. (2018) present a fire monitoring and detection system for tactical forest firefighting operations utilizing unmanned aerial vehicles (UAVs), remote sensing, and image processing. Çolak and Sunar (2020) analyzed fire risk in the Menderes region, İzmir, Turkey, using remote sensing technology by integrating pre-fire remote sensing data with ancillary data in GIS, with which the spatial and temporal patterns of forest fire risk were evaluated. Land surface temperature (LST) changes and in situ meteorological measurements were used to assess the rapid fire risk, and a linear model incorporating six fire risk variables was applied to generate a fire risk map. The model was validated by overlaying historical forest fire data on the fire risk map, demonstrating its effectiveness in identifying high- and moderate-high-risk areas. Lee et al. (2017) revealed that traditional methods of wildfire monitoring, such as manned airplanes and satellite images, have limitations in terms of cost, temporal resolution, and spatial resolution. To address these challenges, a wildfire detection system utilizing unmanned aerial vehicles (UAVs) and deep convolutional neural networks (CNNs) was developed, providing cost-effective, high-resolution images for early wildfire detection. The system demonstrated high accuracy across a wide range of aerial photographs, enabling more effective wildfire monitoring and response efforts.

The Fire Information for Resource Management System (FIRMS) (Fig. 6.3) is a comprehensive online tool developed by NASA that provides valuable information and real-time monitoring of wildfires worldwide (Davies et al. 2008). FIRMS utilizes satellite data to detect and track active fires, providing users with up-to-date information on fire locations, intensities, and associated data such as fire radiative power and thermal anomalies. The system integrates data from various satellite sensors, including MODIS and VIIRS (Riggs et al. 2017), to provide a comprehensive and accurate picture of wildfire activity. It offers a user-friendly interface that allows users to access fire information through an interactive map. The map displays fire hotspots and allows users to zoom in and obtain detailed information about specific fires. Additionally, FIRMS provides data on fire emissions, smoke plumes, and

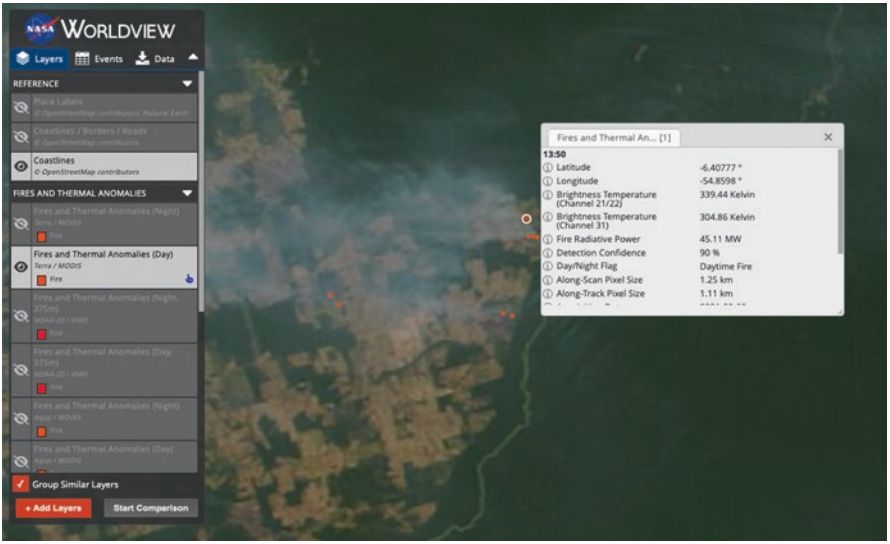


LATITUDE	LONGITUDE	BRIGHTNESS	SCAN	TRACK	ACQUIRE_TIME	CONFIDENCE	VERSION	BRIGHTNESS2	FRP	DAYNIGHT
53.20131	-116.28036	300.21	2.08	1.4	2023-05-21 07:00:00	22	6.1NRT	281.96	20.35	N

Fig. 6.3 FIRMS interface (NASA Fire Information for Resource Management System) – MODIS and VIIRS active fire/thermal anomaly data may be from fire, hot smoke, agriculture, or other sources

other fire-related parameters, enabling scientists, emergency responders, and land managers to assess the impact of wildfires on the environment, air quality, and human health. The data provided by FIRMS are essential for wildfire management and resource allocation. The system enables early detection of wildfires, facilitating rapid response and firefighting efforts. It helps authorities identify high-risk areas, monitor fire behavior, and make informed decisions regarding evacuation orders and resource deployment. Moreover, FIRMS aids in post-fire analysis and recovery efforts by providing historical fire data and assessing fire severity.

Another major fire information platform from NASA, Worldview, offers access to a wide range of satellite imagery, including fire data, for monitoring and analyzing wildfires across the globe (Fig. 6.4). It also provides a user-friendly interface that allows users to visualize and analyze fire-related information in near real time. The fire data available in Worldview is derived from the similar satellite sensors like MODIS and VIIRS, which capture thermal signatures and detect active fires. Worldview allows users to monitor the location, extent, and intensity of active fires. This information is crucial for assessing fire behavior, identifying areas at risk, and monitoring the progression of fire events over time. It enables fire managers, emergency responders, and land management agencies to make informed decisions regarding fire suppression efforts, resource allocation, and evacuation strategies. During and after wildfire events, Worldview's fire data can aid in disaster response and recovery efforts. It helps assess the extent of fire-affected areas, track fire perimeter growth, and identify areas of high severity. This information assists in evaluating the damage caused by wildfires, assessing infrastructure vulnerability, and prioritizing post-fire recovery and rehabilitation activities. It empowers decision-makers, researchers, and the general public with timely and comprehensive



13:50

Latitude	-6.40777 °
Longitude	-54.8598 °
Brightness Temperature (Channel 21/22)	339.44 Kelvin
Brightness Temperature (Channel 31)	304.86 Kelvin
Fire Radiative Power	45.11 MW
Detection Confidence	90 %
Day/Night Flag	Daytime Fire
Along-Scan Pixel Size	1.25 km
Along-Track Pixel Size	1.11 km

Fig. 6.4 NASA Worldview fire and thermal detection

information to mitigate the risks associated with wildfires and promote effective fire management strategies.

While remote sensing-based systems like FIRMS and Worldview are valuable assets, there are certain limitations that cannot be ignored. Satellite imagery used in these systems usually have coarse spatial resolution, making it challenging to detect and monitor small-scale fires or fires in remote areas accurately. Additionally, the temporal resolution may vary depending on the satellite sensor, resulting in delays in detecting and reporting fire events. Cloud cover and smoke can obstruct satellite imagery, reducing the effectiveness of fire detection and monitoring. Thick smoke can obscure fire signatures and make it challenging to accurately assess the extent and intensity of fires. Similarly, cloud cover can limit the availability of clear imagery, especially in regions with persistent cloud cover or during certain seasons. Remote sensing-based fire products may encounter false positives (incorrectly identifying non-fire features as fires) or false negatives (missing actual fire events). Various factors can contribute to these errors, including the presence of hotspots unrelated to fires (e.g., industrial activities) or the inability to detect fires due to limitations in sensitivity or atmospheric conditions. Additionally, remote sensing may have limitations in providing detailed information on fire behavior, such as fire spread rate, fireline intensity, or ember showers. These details are crucial for fire management and decision-making but may require ground-based observations or other specialized tools for accurate assessment. Depending on the remote sensing system and data processing workflows, there may be a delay in accessing and disseminating fire data. Real-time data availability can be critical for timely decision-making during active fire events, and any delays in data processing or accessibility can hinder effective fire management efforts. Another important factor is that remote sensing-based fire products rely on satellite observations, and ground validation for verifying the accuracy and reliability of the detected fire events. However, ground-based observations may not always be feasible due to remote or inaccessible fire locations, posing challenges in validating the remote sensing-derived fire data. These reasons are greatly limiting the actionableness of using remote sensing tools in practical wildfire firefighting.

3.2 Sensor Networks and Real-Time Data Collection

There are many ground operational networks that can support wildfire early warning and monitoring. RAWS (Remote Automated Weather Stations) is a network of weather stations (Fig. 6.5) strategically placed in wildfire-prone areas (Nauslar et al. 2018). These stations continuously monitor weather conditions such as temperature, humidity, wind speed, and precipitation, providing valuable data for assessing fire danger and supporting early warning systems. The National Weather Service also operates a network of weather stations across the United States. These stations provide real-time weather data, including temperature, humidity, wind speed, and atmospheric conditions, which are critical for monitoring and predicting fire behavior. These networks provide data on rainfall, streamflow, soil moisture, and other factors that can help assess fire risks and predict potential fire behavior. EONET (Earth Observatory Natural Event Tracker), managed by NASA, is a global system that collects and shares information on various natural hazards, including wildfires (Ward 2015). It aggregates data from multiple sources, including ground-based sensors, satellite imagery, and other remote sensing technologies, to provide real-time updates on wildfire events worldwide. FLIR (Forward-Looking Infrared) networks utilize infrared technology to detect and monitor heat signatures associated with wildfires (Khan et al. 2009). These networks consist of ground-based or aerial-based sensors that can detect hotspots and track fire progression, providing valuable information for early detection and response. Besides these officially maintained networks, citizen science initiatives involve engaging the public in data collection and monitoring efforts. Platforms such as iNaturalist and eBird allow individuals to report wildfire observations and contribute to a collective understanding of fire events. These initiatives can supplement ground-based sensing networks and provide additional data points for monitoring and early warning systems.

Barmpoutis et al. (2020b) proposed the use of 360-degree sensor cameras for early fire detection. The approach involves converting equirectangular projection format images to stereographic images and utilizing DeepLab V3+ networks (Chen et al. 2018) for flame and smoke segmentation. Experimental results demonstrate the system's effectiveness, achieving a high F-score fire detection rate of 94.6% and showcasing its potential contribution to early fire detection while reducing the number of required sensors. Ahlawat and Chauhan (2020) highlight the utilization of wireless sensor networks (WSNs) for forest fire detection and information monitoring. The authors propose an efficient real-time setup that collects information from

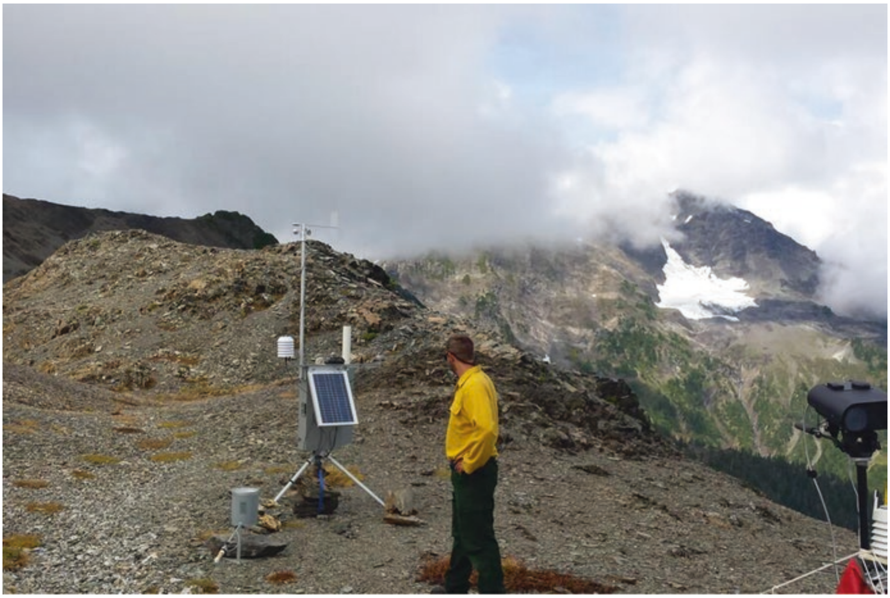


Fig. 6.5 RAWS station with wildfire closeby. (Image courtesy: https://www.nifc.gov/about-us/what-is-nifc/remote-automatic-weather-stations)

different locations and uploads it to a remote web server. Using Wi-Fi and NodeMCU micro-controller with built-in ESP 8266 Wi-Fi module, communication is established within the network and the proposed solution is implemented on the Arduino Integrated Development Environment (IDE) (Srivastava et al. 2018). Abdullah et al. (2017) present a compact, energy-efficient sensor network that combines various sensory inputs for continuous monitoring of forest environments and early detection of fires, and successfully tested in a real-life firefighting trial, showing promising results for coordinated firefighting scenarios. Lutakamale and Kaijage (2017) present a wildfire monitoring and detection system that utilizes a wireless sensor network that monitors temperature, humidity, and smoke to detect fires, and immediately sends a warning message with the probable location to the responsible authority via a cellular network. The system prototype, developed using Arduino microcontroller and various sensors, demonstrates the capability to detect wildfires in real time, making it an effective solution for early wildfire detection and reporting. Kadir et al. (2019) propose the development of wireless sensor networks (WSNs) for detecting forest fire hotspots in Indonesia, focusing on the high-risk region of Riau Province. WSNs are used as ground sensor systems to collect environmental data, which is then analyzed in the data center to identify fire hotspots and potential fire risks. The deployment of sensors in strategic locations, along with mathematical analysis, enhances the feasibility and effectiveness of early warning and alert systems for forest fire detection and prevention in Indonesia. Doolin and Sitar (2005) present the design and field testing of a wireless sensor system for monitoring wildfires, using environmental sensors to collect temperature, humidity, and barometric pressure data. The system performed well during prescribed burns, capturing the passage of the flame front, temperature changes, humidity decreases, and barometric pressure drops. The recorded data indicated the development of locally significant weather conditions even during relatively cool grass fires, with maximum temperature reaching 95 °C, minimum relative humidity of 9%, and a significant drop in barometric pressure. Somov (2011) conducted a survey of approaches for early wildfire detection using wireless sensor networks (WSNs), with a focus on real deployments and hardware prototypes. The methods are categorized into gas sensing, environmental parameter sensing, and video monitoring, and are analyzed based on cost, power consumption, and implementation complexity. Slavkovikj et al. (2014) discussed the current systems and methods for utilizing social media data in wildfire detection and management, highlighting their potential and examining approaches from other hazard management systems. They also proposed a general social sensor-based platform for wildfire detection and management. Barrado et al. (2010) presented a pervasive application for fighting forest fires that utilizes unmanned aircraft, personal electronic devices (PEDs), and a three-layered communication network. The system enables firefighters to obtain temperature maps of burned areas, locate hot spots, and receive commands from their manager in real time, contributing to more effective decision-making and firefighting efforts.

Although these research all demonstrated promising results, they may not be immediately actionable in real-world wildfire responding due to various reasons. First, the proposed approaches involve advanced techniques, complex algorithms, or specialized hardware that are not readily available or easily implemented in practical firefighting operations. The results were obtained in controlled experimental environments or small-scale deployments, but scalability and successful deployment in larger, real-world scenarios could pose significant barriers. The implementation of certain solutions requires significant financial resources, infrastructure, or expertise that are infeasible within the budget or operational capabilities of firefighting agencies. The proposed systems may need further validation, testing, and refinement to ensure their reliability, robustness, and resilience in challenging and dynamic wildfire environments. The compatibility and integration of the proposed solutions with existing firefighting systems, protocols, and networks may need to be addressed for seamless adoption and practical implementation.

3.3 Application of Computer Models and Simulations in Predicting Wildfire Behavior

Duff and Tolhurst (2015) examine the development of operational models that simulate fire suppression as part of decision support systems. The authors summarize the progress in modeling approaches, discuss their strengths and limitations, and offer insights into future research directions. Hanson et al. (2000) focus on recent developments in computer models of wildfires and their potential application in mitigating the threat. The article also discusses the need for an operational wildfire prediction center to harness existing capabilities and develop new tools for addressing this natural process. Monedero et al. (2019) developed the Wildfire Analyst™ Pocket Edition application (WFA Pocket), a mobile tool designed for firefighters, providing real-time, interactive 3D maps that display fire characteristics and estimated progression based on user input data. The application integrates GIS capabilities, can be used online or offline, and retrieves fuel, weather, and canopy data from online servers. Marsavin et al. (2023) used Convolutional Long Short-Term Memory (ConvLSTM) networks to model fire progression dynamics in space-time and achieved impressive effectiveness. Zhai et al. (2020) presented a learning-based wildfire spread model that combines real-time rate of spread (RoS) measurement with machine learning and a level-set method to predict short-term wildfire spread. The model is validated through comparisons with experimental measurements and applied to a real-scale shrubland fire scenario. Results demonstrate the capability of the proposed method to predict fire spread without relying on empirical RoS models, offering potential benefits for modeling real wildfires. Papadopoulos and Pavlidou (2011) investigated the use of discrete event models and simulators to study complex phenomena in ecosystems, with a specific focus on forecasting forest fire propagation. Twenty-three simulators are reviewed, and the FARSITE simulator model is identified as the most noteworthy and extensively evaluated in a test environment. Rashid et al. (2020) introduced the CompDrone framework, which combines computational wildfire modeling with social-media-driven drone sensing (SDS) for improved wildfire monitoring. By leveraging techniques from cellular automata, constrained optimization, and game theory, CompDrone addresses the challenges of limited social signals and predicting optimal drone dispatch regions. Porterie et al. (2005) developed a physical two-phase to simulate wildland fire behavior and emissions, considering the dynamics, turbulence, soot formation, and radiation. The model successfully captured the rate of spread and fuel consumption ratio of a prescribed savanna fire, demonstrating good qualitative agreement with in situ experimental data. Bakhshaii and Johnson (2019) explained the evolution of wildfire models, specifically the transition to mechanistic combustion models and large-eddy simulation (LES) coupled with computational fluid dynamics (CFD) or mesoscale weather models. These integrated models, which consider fuel, terrain, and weather conditions, represent the next generation of wildfire modeling and are designed for specific spatial and temporal scales. Lopes et al. (2002) developed FireStation for simulating fire spread over complex topography. It incorporates a semi-empirical model for fire rate of spread, wind field simulation, and a user-friendly graphical interface. The system aims to facilitate operational fire behavior prediction and has shown promising results when compared to experimental data.

However, similar to all the other numerical models, wildfire models have the same restrictions when being used to guide real-world operations. The uncertainties due to limitations in input data, parameterization, and the inherent complexity of fire behavior can affect the accuracy and reliability of the model predictions. Wildfire behavior involves a range of complex physical processes, including combustion, radiation, and turbulence. Capturing all these processes accurately in numerical models can be challenging, and simplifications or assumptions may be necessary, which can introduce uncertainties. The resolution of numerical models may not capture fine-scale variations in fire behavior, such as spot fires or localized wind patterns. This can lead to limitations in accurately predicting fire spread and behavior at smaller scales. Validating and calibrating numerical models require accurate and extensive field data, which may not always be available. Limited validation can impact the reliability and confidence in model outputs. Meanwhile, numerical models for wildfire behavior are sensitive to input parameters, such as fuel moisture, wind speed, and topography. Small errors or uncertainties in these parameters can significantly affect the model outputs, leading to inaccuracies in fire spread predictions. On the cost-wise side, running numerical models for wildfire behavior can be computationally demanding and time-consuming, especially for large-scale simulations or simulations with high spatial and temporal resolutions (Rodriguez-Aseretto et al. 2013). This can limit the practicality and real-time applicability of the models in operational firefighting scenarios. From the operational perspective, the effective use of numerical model outputs for wildfire operations relies on the expertise and interpretation of the end users. Understanding and properly interpreting the model outputs require knowledge and experience in wildfire behavior, which may not be available to all personnel involved in firefighting operations. Also, translating complex model outputs into meaningful and actionable information for decision-makers can be a challenge. Clear communication and effective visualization of the model results are crucial to ensure the usability and understanding of the information by operational personnel. Scientists have to tackle all these issues to make their research more actionable.

3.4 Next-Generation Firefighting Techniques

Scientists never stop finding new solutions to more effectively contain fires. There are many new potential or emerging technologies that might be the next game changer. For example, drones equipped with specialized sensors and cameras can provide real-time situational awareness, thermal imaging, and aerial surveillance of wildfire incidents (Sousa et al. 2020). UAS can assist in identifying fire hotspots, monitoring fire behavior, and guiding firefighting efforts more effectively. The recent development of new fire-resistant materials, such as fire-resistant gels, foams, and coatings, can be applied to structures, equipment, and vegetation to provide enhanced fire protection. These materials can reduce the flammability of surfaces and slow down the spread of fire. Other innovations in fire-resistant fabrics and personal protective equipment (PPE) can greatly improve the safety and effectiveness of firefighters (Song et al. 2016). Advanced materials can provide increased heat resistance, improved breathability, and better protection against radiant heat and flames. Researchers are actively looking for new fire-suppression agents, including environmentally friendly alternatives. These agents aim to improve firefighting effectiveness by increasing extinguishing capabilities, reducing environmental impact, and enhancing safety for both firefighters and the ecosystem. At a larger scale, implementing fire-resistant landscaping practices, such as strategically planting fire-resistant vegetation, creating firebreaks, and using noncombustible materials around structures, can help reduce the spread of wildfires and protect vulnerable areas. As for the inaccessible area for humans, autonomous or remotely operated robotic systems designed for firefighting can access hazardous areas and perform tasks that may be too dangerous for human firefighters. These robots can deploy fire suppressants, gather data, and assist in fire suppression efforts.

Aydin et al. (2019) explore the use of fire extinguishing balls in conjunction with drones and remote sensing technologies as a supplemental approach to traditional firefighting methods. The proposed system includes scouting unmanned aircraft systems (UAS) for detection and monitoring, communication UAS for establishing communication channels, and firefighting UAS for autonomously delivering fire extinguishing balls. The experiments conducted so far indicate that while smaller-sized fire extinguishing balls may not be effective for building fires, they show promise in extinguishing short grass fires, which has guided the authors toward focusing on wildfire fighting. The paper also discusses the development of heavy payload drones and the progress in building an apparatus to carry fire-extinguishing balls attached to drones. Bordado and Gomes (2007) overviewed that synthetic polymers and superabsorbent polymers have shown significant advancements and potential in various fields, including agriculture and fire suppression. However, it is important to consider their environmental impact, proper application, and potential limitations in specific scenarios. New aerosol-based fire extinguishing systems (Rohilla et al. 2022) have gained popularity due to their effectiveness and ease of use. These aerosols contain fine particles that can quickly suppress fires by interrupting the chemical chain reaction. They are particularly useful in enclosed spaces and electrical fires. Traditional foam agents used in firefighting contain harmful chemicals such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS). Innovations have led to the development of eco-friendly foam agents that are free from these toxic substances (Pierau et al. 2022). These foam agents maintain their fire suppression capabilities while reducing environmental impact. Water mist systems use fine droplets of water to suppress fires (Lazzarini et al. 2000). These systems are effective in controlling fires by cooling the flames, reducing the oxygen supply, and preventing the fire from spreading. Water mist systems are especially useful in environments where water damage needs to be minimized, such as data centers and heritage buildings. Clean agent fire suppressants, such as halocarbon-based gases, are used to extinguish fires without leaving residue or causing damage to sensitive equipment (Sebastian2022). These agents work by displacing oxygen and interrupting the combustion process. They are commonly used in areas where water or foam-based suppression systems may cause more harm than the fire itself. Another technology is powder-based fire extinguishers that have been used for a long time, but advancements have led to the development of more effective and specialized powders (Du et al. 2019). These powders, such as monoammonium phosphate (MAP) and potassium bicarbonate, are capable of suppressing various types of fires, including those involving flammable liquids, electrical equipment, and combustible metals.

Future technology like nanotechnology has opened up new possibilities for fire suppression (Mosina et al. 2020). Nanoparticles, such as graphene and nanoclay, have shown promise in enhancing the extinguishing properties of traditional fire suppressants. They improve heat transfer, increase the surface area coverage, and enhance the overall fire suppression capabilities. Other relevant technical breakthroughs like fire-resistant coatings (Gan et al. 2020) can be used to provide passive fire protection by delaying the spread of flames and reducing heat transfer. These coatings can be applied to various surfaces, including walls, ceilings, and structural elements. They help to buy critical time for evacuation and firefighting efforts. Advancements in sensor technology and artificial intelligence have led to the development of smart fire detection and suppression systems (Neumann et al. 2018). Researchers are also exploring the use of bio-based materials, such as plant extracts and biodegradable compounds, as fire suppressants (Kalali et al. 2019). These eco-friendly alternatives aim to reduce the environmental impact of fire extinguishing agents while maintaining effective fire suppression properties.

4 Case Studies and Success Stories

4.1 Examples of Successful Application of Actionable Science in Wildfire Management

Advanced technologies, such as remote sensing, weather forecasting, and satellite imagery, are widely utilized to develop early warning systems for wildfires. These systems enable authorities to detect and predict fire behavior, allowing for early evacuation and proactive firefighting strategies. The Fire Integrated Real-Time Intelligence System (FIRIS) in California (Altintas 2021) combines satellite data, weather information, and ground sensors to provide real-time situational awareness during wildfires, assisting fire managers in decision-making and resource allocation. For example, in the Thomas Fire, which is one of the largest wildfires in California's history and burned over 281,000 acres (Dahill 2019), FIRIS was utilized to monitor fire behavior, track its progression, and assess the potential threats to communities. The system integrated data from satellites, weather stations, and ground sensors to provide accurate information to incident commanders. This allowed firefighting resources to be deployed effectively and facilitated timely evacuation orders. During the Mendocino Complex Fire, comprising the Ranch Fire and the River Fire, and the largest recorded wildfire complex in California, consuming more than 459,000 acres (Scalingi 2020), FIRIS provided up-to-date information on fire behavior, hotspots, and fire spread patterns and helped incident managers make informed decisions on resource allocation, air operations, and firefighter safety. In the Bobcat Fire that burned over 115,000 acres in the Angeles National Forest

(Seeberger 2020), FIRIS was used extensively to monitor fire behavior, identify critical fire perimeters, and assess potential threats to infrastructure, communities, and sensitive ecosystems. The system's data and visualizations aided incident commanders in determining containment strategies and allocating firefighting resources effectively.

The Canadian Forest Fire Behavior Prediction (FBP) System is widely used to estimate fire behavior in Canada. It incorporates factors like fuel moisture, wind speed, and slope to predict fire spread and intensity, aiding in proactive fire management. During the devastating Fort McMurray wildfire in Alberta, Canada, the FBP System is used to predict fire behavior and aid firefighters and incident management teams to understand the fire's spread, plan evacuations, and allocate resources effectively. In British Columbia, Canada, the FBP System's ability to predict fire behavior helps in effective resource allocation and evacuation planning. By understanding how a fire is likely to spread, incident management teams can allocate firefighting resources strategically and evacuate areas at risk in a timely manner, ensuring the safety of residents and responders. In Ontario, Canada, the FBP System is employed during large-scale wildfires to assist with resource management and evacuation planning. During the Parry Sound 33 wildfire in 2018, the FBP System provided valuable information about fire behavior, which helped authorities make decisions about evacuation orders and allocate firefighting resources effectively.

The National Fire Plan in the United States emphasizes fuel reduction efforts, such as the use of controlled burns and mechanical treatments, to reduce fire risk. The implementation of these strategies has proven successful in mitigating wildfire impacts. The NFP provided support for fire suppression efforts and post-fire rehabilitation for many wildfires such as Hayman Fire (2002) (Graham 2003), Shasta-Trinity Complex Fire (2008), Wallow Fire (2011), and Rim Fire (2013). The Hayman Fire started on June 8, 2002, in Park County, Colorado. Despite an aggressive initial attack response, the fire rapidly spread due to high winds, low humidity, and dry fuel conditions. The severe drought and continuous fuel across the landscape contributed to extreme fire behavior, including torching trees and prolific spotting, resulting in the fire crossing U.S. Highway 77. The Firewise USA program, initiated by the National Fire Protection Association (NFPA), encourages communities to implement wildfire mitigation measures. Participating communities receive science-based guidance on defensible space creation and community planning to reduce wildfire vulnerability. The Firewise USA program has been implemented in various communities of California to enhance their resilience to wildfires. For instance, the Lake Almanor Peninsula Firewise Community in Plumas County has actively participated in the program, implementing measures such as vegetation management, community education, and collaboration with local fire agencies to reduce the risk of wildfires. Also, the Firewise USA program has made a significant impact in communities like Boulder County, Colorado. The Coal Creek Canyon Fire Protection District, a Firewise community, has actively worked to create defensible spaces by conducting wildfire assessments, hosting educational workshops, and coordinating fuel reduction projects. These efforts have helped safeguard homes and reduce the potential for wildfire damage.

4.2 Real-World Stories Highlighting the Benefits of Science-Based Approaches

First, we may take a look at the Rim Fire (2013). The Rim Fire, which started on August 17, 2013, in California's Stanislaus National Forest (Jenner 2013), became one of the largest wildfires in the state's history, burning over 257,000 acres. Fire behavior analysts utilized scientific methods to study the fire's behavior, taking into account weather patterns, topography, fuel conditions, and historical fire data. By analyzing these factors, they were able to predict the fire's potential spread and intensity. Advanced fire modeling techniques, such as the Weather Research and Forecasting model coupled with fire behavior models (WRF-SFIRE) (Mandel et al. 2014), were employed to simulate fire behavior under different weather scenarios. This allowed fire managers to anticipate fire growth patterns and strategically allocate firefighting resources. Satellite-based sensors, such as NASA MODIS, provided real-time data on the fire's perimeter, heat signatures, and smoke plumes. This information was crucial in identifying fire hotspots and prioritizing firefighting efforts. The Rim Fire saw the deployment of aerial firefighting resources, including air tankers and helicopters. Scientifically informed strategies were used to determine the most effective locations for fire retardant drops and water bucket deployments. This targeted approach helped create firebreaks and slow the fire's progression. Firefighters and fire managers used scientific knowledge to strategically construct containment lines, considering factors such as topography, fuel conditions, and predicted fire behavior. These containment lines served as physical barriers to prevent the fire's spread and protect communities and critical infrastructure. After the fire was contained, scientific approaches were employed to assess the impacts on the ecosystem and develop restoration plans. Scientists studied the fire's effects on vegetation, soil erosion, and wildlife habitat to guide post-fire rehabilitation efforts. This involved activities such as reseeding native plants, erosion control measures, and monitoring of ecosystem recovery. The success in containing and managing the Rim Fire was a result of collaborative efforts between fire managers, scientists, and various agencies. Scientists provided valuable insights and recommendations based on their expertise, which informed decision-making processes throughout the firefighting and restoration efforts.

Let us shift our attention to the wildfires in other countries. The Black Saturday Bushfires, which occurred on February 7, 2009, in the state of Victoria, Australia, were one of the most devastating wildfire events in the country's history, resulting in the loss of 173 lives and the destruction of thousands of homes (Whittaker et al. 2013). Advanced predictive models, such as the Phoenix RapidFire software, were employed to simulate fire behavior and potential ember attacks under different weather scenarios. This information was crucial in understanding the risks and aiding in decision-making related to firefighting efforts, including the deployment of resources and prioritizing high-risk areas. Science-based early warning systems, such as the Victorian Fire Risk Register (VFRR) and the Country Fire Authority (CFA) FireReady app (Bowen 2020), provided real-time fire updates and warnings to communities. These systems utilized scientific data, including weather forecasts, fire behavior models, and satellite imagery, to issue timely alerts, enabling residents to evacuate early and emergency services to respond more effectively. The knowledge of fire behavior and resource effectiveness informed the deployment of aerial firefighting resources, such as water-bombing aircraft and helicopters.

5 Actionable Science Suggestions for Wildfire Researchers and Stakeholders

Based on the observation and analysis, combining with our formula from Chap. 1, we provide some suggestions for scientists to consider to improve the actionableness of wildfire research.

5.1 Addressing the Real Gap in Implementing Actionable Science for Wildfires

While fundamental research is valuable, scientists should also focus on applied research that directly addresses practical challenges faced in wildfire management. This includes studying specific fire behavior phenomena, developing and testing new tools and technologies, and evaluating the effectiveness of different management strategies. Researchers should prioritize the dissemination of their findings in a format that is accessible and useful for practitioners. This includes publishing research in peer-reviewed journals, but also developing concise and practical summaries, guidelines, and toolkits that can be easily understood and implemented by those working in the field. Meantime, by focusing on applied research that directly addresses practical challenges faced in wildfire management, scientists can provide solutions and insights that are immediately relevant to the field. This type of research takes into account the specific needs and constraints of practitioners, helping them make informed decisions and take effective actions. Studies that investigate the behavior of firebrands (burning embers) during wildfires can have more practical implications for firefighters and community planning (Caton et al. 2017). Understanding real demands by ground teams like how firebrands are transported by winds and ignite spot fires can lead to improved firefighting strategies, such as positioning fire engines strategically to prevent spot fire ignitions. About technology, adopting and testing new tools such as unmanned aerial systems (UAS), or drones, equipped with thermal cameras and multispectral sensors, allows researchers to provide practical solutions for enhanced fire detection, monitoring, and response. By collaborating with engineers and technologists, scientists can translate their knowledge into tangible innovations that can be readily implemented in the field. Last but not least, the world is constantly changing, and so will the firefighting strategy. Science guidance should have room for change of plans and think about as many situations as possible. Evaluating the effectiveness of different management strategies used in wildfire prevention, suppression, and mitigation provides evidence-based insights for decision-making. By assessing the outcomes of these strategies, scientists can inform policymakers and practitioners about the most effective approaches, leading to more efficient and targeted wildfire management efforts.

5.2 Research Gaps and Areas for Further Exploration

While significant progress has been made in wildfire research, there are still several research gaps and areas for further exploration that are the key questions from the operators but not yet fully answered by scientists. We hope researchers can prioritize these areas to get them solved to tackle the urgent demands on the field. These gaps arise due to various challenges, limitations, and complexities associated with wildfires. The first gap is we are still trying to understand the influence of climate change on wildfire behavior and dynamics (De Rigo et al. 2017). Research needs to explore the complex interactions between climate drivers, such as temperature, precipitation, and wind patterns, and their effects on fuel availability, fire frequency, and intensity. However, predicting future climate scenarios and their specific impacts on wildfires is challenging as climate models have uncertainties and localized effects can vary significantly. On the other side, while immediate fire impacts, such as direct damage to ecosystems and infrastructure, are well-studied, there is a need for research on the long-term ecological and socioeconomic effects of wildfires. This includes studying the recovery and regeneration processes of fire-affected landscapes, as well as the socioeconomic impacts on local communities and their resilience in the aftermath of wildfires. Long-term studies require sustained monitoring efforts and may take years to gather meaningful data. Third major question is about the role of humans in the whole cycle. Understanding human behavior, attitudes, and decision-making during wildfires is critical for effective fire management. Research should explore the social, cultural, and economic factors that influence wildfire preparedness, evacuation decisions, and community resilience. However, collecting data on human behavior and conducting comprehensive social science research in high-stress disaster situations can be challenging due to ethical considerations and logistical constraints. In addition, the WUI (Wildland-Urban Interface) (Radeloff et al. 2005), where human developments meet wildland areas, is particularly vulnerable to wildfires. Further research is needed to understand the dynamics of fire spread in the WUI, the effectiveness of different mitigation strategies, and the social and economic factors that influence decision-making and community engagement. However, implementing actionable solutions in the WUI requires coordination among multiple stakeholders, including homeowners, local governments, and land management agencies, which can present logistical and political challenges.On the technology challenge, advances in remote sensing technologies and predictive modeling have greatly enhanced our understanding of wildfire behavior. However, there is still a need for research to improve the accuracy, resolution, and timeliness of remote sensing data, as well as the reliability of predictive models. Additionally, translating these technological advancements into operational tools that can be effectively used by fire management agencies and practitioners requires further development and refinement. As for public health, wildfires generate significant amounts of smoke, which poses health risks and air quality concerns. Research should focus on developing effective smoke management strategies, including improved smoke forecasting, modeling, and communication systems. However, implementing smoke management practices involves coordination among multiple agencies, consideration of local air quality regulations, and public education efforts, which can present logistical and policy challenges.

As these questions are challenging but we are very urgently craving for answers, research on these topics will receive very high expectations for action conversion rate whenever there is a breakthrough. It is essential for researchers, policymakers, and practitioners to collaborate and actively communicate research findings to ensure that breakthroughs lead to actionable outcomes. By considering real-world challenges, stakeholder needs, and the practical feasibility of implementing research outcomes, scientists can increase the likelihood of their work translating into effective wildfire management strategies.

5.3 Importance of Interdisciplinary Collaboration, In-Time Sharing, and Transparent Communication

Wildfire management is a complex and multidisciplinary field, requiring expertise from various disciplines such as ecology, meteorology, social sciences, and engineering (Bonebrake et al. 2018). Scientists should actively seek out interdisciplinary collaborations to address the diverse aspects of wildfire management and integrate different perspectives into their research. Scientists should actively engage and collaborate with firefighters, land managers, and other stakeholders involved in wildfire management. By working together, they can ensure that research aligns with the needs and realities of on-the-ground fire management, making it more relevant and applicable. Scientists should actively participate in knowledge exchange activities, such as conferences, workshops, and field demonstrations, where they can share their research findings and learn from practitioners. This two-way exchange of knowledge can help researchers gain insights into real-world challenges and refine their research to be more applicable. One example of successful knowledge exchange is the Joint Fire Science Program (JFSP) in the United States (Fig. 6.6) (Maletsky et al. 2018), which supports research projects that address the needs of fire managers and practitioners. The JFSP facilitates collaboration between scientists and land managers, ensuring that research findings are directly applicable to on-the-ground fire management.

JOINT FIRE SCIENCE PROGRAM

AN INTERAGENCY RESEARCH, DEVELOPMENT, AND APPLICATIONS PARTNERSHIP

The JFSP provides funding for scientific studies associated with managing wildland fuels, fires, and fire-impacted ecosystems to respond to emerging needs of policymakers, managers, and practitioners.

The 15 Fire Science Exchanges are:

- Alaska Fire Science Consortium
- Consortium of Appalachian Fire Managers and Scientists
- California Fire Science Consortium
- Great Basin Fire Science Exchange
- Great Plains Fire Science Exchange
- Lake States Fire Science Consortium
- North Atlantic Fire Science Exchange
- Northern Rockies Fire Science Network
- Northwest Fire Science Consortium
- Oak Woodlands and Forests Fire Consortium
- Pacific Fire Exchange
- Southern Fire Exchange
- Southern Rockies Fire Science Network
- Southwest Fire Science Consortium

Fig. 6.6 The science exchanges supported by JFSP. (Image courtesy: https://www.firescience.gov)

Also, another very important task (no need to say) is that scientists should actively seek funding opportunities that prioritize actionable research on wildfires. Governments, research agencies, and foundations often provide grants and funding for research projects that address pressing issues and have practical applications in managing wildfires. For example, the European Commission's Horizon 2020 program (Pollex and Lenschow 2018) has funded projects like FIREFLIES and PyroLife, which focus on improving fire management practices through interdisciplinary research and innovation.

6 Conclusion

In the field of wildfire management, there is a growing recognition of the need for actionable science to bridge the gap between researchers and operational teams. Currently, wildfire management practices rely on a combination of experience, expertise, and available knowledge, but there is room for improvement. Scientists are actively addressing this gap by conducting research that directly addresses practical challenges faced in wildfire management. The focus is on studying specific fire behavior phenomena such as fire spread, ignition patterns, and fire–atmosphere interactions, developing and testing new tools and technologies, and evaluating the effectiveness of different management strategies. By studying these specific phenomena, scientists can provide valuable insights and develop predictive models that assist in making informed decisions during firefighting operations. Scientists should also prioritize interdisciplinary collaborations, engage with stakeholders, disseminate findings in accessible formats, and actively seek funding opportunities for actionable research. By adopting these approaches, researchers can enhance the application of their work, leading to more effective and informed wildfire fighting strategies. Most importantly, scientists should actively collaborate with operational teams, firefighters, and land managers to ensure that their research aligns with the needs and realities of on-the-ground fire management. This collaboration will facilitate the integration of scientific findings into operational strategies and enhance the effectiveness of wildfire management practices.

On the other hand, stakeholders and people in wildfire-impacted areas expect significant progress and advancements in the next two decades. They anticipate that scientists will develop innovative and effective strategies to mitigate the impacts of wildfires, including improved early warning systems, better fire behavior prediction models, and more accurate risk assessments. Stakeholders also hope for increased community resilience through better land management practices, enhanced public awareness, and the implementation of fire-resistant construction techniques. Additionally, they expect scientists to contribute to the development of sustainable solutions that balance fire management with ecological conservation. Overall, stakeholders and people in wildfire-impacted areas look forward to seeing science-based approaches integrated into operational practices, resulting in more efficient and effective wildfire management and a safer environment for communities at risk.

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