Wildland Fire Management Interim ConOps v1.0

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1 Executive Summary

This document outlines a concept of operations (ConOps) for a future state of wildland fire prevention, mitigation, and suppression offered as a recommendation and initial guidance for updating current methodologies, technologies, or standards to fit the growing scope of wildland fire. This document serves to collect and summarize the research and work of NASA and other U.S. federal agencies, partner groups, and private industry in envisioning ways, backed by expertise, that could bolster and increase support for firefighting personnel such that overall effectiveness, safety, and efficiency is drastically increased. This document will start with the background of the joint efforts and methods of research and collaboration, followed by a detailed discussion of the current state of wildland fire efforts. In contrast to the current state, the vision for the future state reveals specific areas of improvement with suggestions for potential emerging technologies. With such changes in mind, there is a brief discussion on the impacts of these changes from the systems, organizational, and procedural perspectives, as well as measures by which the effectiveness of this ConOps could be evaluated upon adoption. This is commenced with a general discussion on the various trade-offs considered and areas of improvements. Note, this is the first iteration of this document intended for initial peer review.

2 Scope

The Wildland Fire Management Concept of Operations (ConOps) is intended as a tool to identify and suggest ways that the wildland firefighting community, regulatory bodies, academia, and private industry can facilitate the evolution of wildland firefighting over the coming decades to be more effective, safe, and forward-thinking. This document considers the challenges and gaps, both procedural and technological, in current day operations, and suggests changes that could move the state of the art forward.

As the firefighting community expands operations to tackle larger and more frequent fires, advancements in technology will play a crucial role, along with a range of new procedures, standards, equipment, and other capabilities. This document has been developed with inputs from a large array of government agencies, private industry, academia, and subject matter experts (SMEs). This Concept of Operations document is not intended to prescribe in detail how the proposed changes will be carried out or who should be "in charge" of managing these changes. Rather, it focuses on describing what the "Future State" of wildland firefighting might look like if the desired changes in this document were developed further and implemented in the coming years.

2.1 Identification

This is interim ConOps version 1.0, in the process of writing and internal review.

2.2 Document Overview

The purpose of this document is to advise the wildland fire community and document requirements for a future system that will integrate key technological and procedural developments. The goal of this ConOps is to develop an interagency document to guide consistency of operation priorities, technology adoption, and programmatic alignment for national needs. Ideally, the recommendations in this document should serve as a guide for further development and mission design over the coming decades to support the advancement of wildland firefighting.

Such advancements are motivated by increasingly severe and lengthy fire years, precipitated by the cumulative effects of climate change and years of suppression-heavy methods of wildland management [Adapt to more wildfire in western North American forests as climate changes | PNAS]. Additionally, due to the increase in incidents along the wildland-urban interface new methods of data gathering, information sharing, aircraft safety, and extended aerial operations are necessary to keep up with the increasing rate and severity of the present fire environment.

The paragraphs below contain brief summaries of each of the 10 sections in this document.

Section 1 is the Executive Summary of this ConOps document.

Section 2 Scope summarizes key information about this ConOps. It specifies the version and status of this document and provides brief summaries of the major sections of the document. It also discusses how the ConOps takes a holistic view of the many systems that are in play in wildfire management: a "system of systems." Finally, it describes the methodology used in creating this document, which includes literature review, interviews with Subject Matter Experts (SMEs), and tabletop conferences with representatives from a wide variety of government agencies.

Section 3 Referenced Documents lists documents basic information that underlies the ConOps document as a whole. In particular, it lists the white papers for each of the three use cases that have been studied to date. Additional white papers covering three new use cases will be added in FY 2024. The documents listed in this section are completely different from those cited in the body of this ConOps; those references are listed in *References* at the end of the document.

Section 4 Current State of Wildland Fire in the U.S. focuses on identifying current limitations within wildland firefighting during all stages of the firefighting lifecycle (Pre-Fire, Active Fire, and Post-Fire). Major gaps in current-day operations have been identified through literature reviews, interviews, and tabletop activities. These gaps, and corresponding suggestions for improvements, are detailed in this section.

Section 5 Future State identifies the approaches, technologies, funding, and organizational changes that, if followed, would result in substantive progress in resolving the gaps and challenges identified in *Section 4*. It provides a desired future state based on current and developing technologies that illustrates the art of the possible.

Section 6 Notional System Architecture(s) and Operational Scenarios is currently under construction. A major objective of this ConOps is the development of a system architecture in which notional architectures of end-to-end systems encompassing prediction, sensing, detection, tracking, aerial suppression, and remediation are outlined. These architectures will depict desired capabilities and the requirements needed to create them and can be used as an encompassing guide for improvements of the end-to-end system of wildland firefighting.

Section 7 Summary of Impacts provides a view of the impact that creating new approaches to wildland fire management will have on existing organizations, procedures, and technology.

Section 8 Outcomes: Measures of Effectiveness looks at how to measure the benefits that might or might not be achieved if and when the proposed changes described in this ConOps were implemented. Gathering appropriate data and applying certain statistical techniques would be key.

Section 9 Analysis of Proposed System reviews the major changes that the proposed system would make: what would be added, modified, or removed. The section includes an analysis of the possible disadvantages and limitations that could result and considers possible alternatives and trade-offs.

Section 10 Summary presents, as its name implies*,* a high level summary of the key points raised in this ConOps.

The development of this inter-agency ConOps is being led by the National Aeronautics and Space Administration (NASA), with NASA acting as the facilitator of this document for the other agencies. NASA was identified as the ideal group to begin this effort in the PCAST report [1] and further directed by the Office of Management and Budget (OMB) to develop a Wildland Fire Concept of Operations. The decision to have this effort spearheaded by NASA comes down to three key motivations: 1. NASA has been consistently involved in Earth Science research, which has clear applications to wildland fire management, 2. NASA as an agency is strongly oriented towards research and development, which gives a distinct advantage in developing a forward-thinking Science and Technology roadmap, and 3. NASA is less focused on supporting operations within wildland fire management, and is able to instead focus on the strategic and overarching view of the future. Ultimately, NASA serves as an enabler to flesh out and further develop the future vision that other operations-focused agencies have of the future of wildland firefighting but may not have the resources to develop themselves.

The overarching objective of this ConOps is to help the firefighting community continue to do their jobs safely and efficiently while at the same time making the necessary transition to a future state with advancements in technologies, practices, and systems. The firefighting community and agencies which conduct wildland fire operations and research are the primary audience of this document. Tabletop discussions and workshops have been conducted during the development of this ConOps to solicit feedback from these groups, and we have seen involvement from many federal, state, and tribal organizations as well as industry.

2.3 System Overview

Managing wildland fires involves many activities in mitigation, active response, and recovery that are discussed throughout this document. Each of these activities are part of a larger whole that has been described as a “system of systems.” This ConOps focuses on wildland fire, but the concepts may be applied to natural disaster and emergency response.

At present, there is no general matter of operations or standard way to respond or mitigate wildland fire, which presents risk of confusion. Practices vary depending on whether the land is private, state, federal, tribal, close to populate areas, remote, dry, humid, accessible by road or foot, etc. This complexity is compounded by the unpredictable nature of wildland fires. There is no simple combination of actors or tools that can cure every wildland fire. In an ideal world, all actors would have perfect situational awareness, allowing all to make informed decisions. This would require that every participant involved to have access to a universal set of date, filtered and displayed to the specific needs to each participant. It also would require connectivity to be ubiquitous, available everywhere and at all times. This ultimate vision is a slow integration of existing capabilities and future technology through all actors involved in wildland fire management, operational systems, information systems, communication means, and coordination between these interfaces. For this system to be universal, there are actors that must be considered beyond just the firefighters. For example, the airspace management of all participating aircraft requires collaboration with all other airspace users and air traffic control (ATC) or communications with the general public.

In order to assess existing procedures, the discussion must first assume existing procedures can be conducted under the current circumstances. This analysis will assume real-time, redundant, information distribution that is unaffected by changes in the firefighting environment or the amount of information. Connectivity is a known obstacle to the wildland firefighting community and this study will address this issue in a use case that will be studied and integrated into a future version of the ConOps.

2.4 Methods of Development

The ConOps development is overseen by an inter-agency working group, consisting of federal, state, and local agencies. The goal of this group is to maintain a universal vision for adopting and integrating technology in support of the wildland firefighting community. As a member of this group, NASA is bringing together expertise from science, applications, space, and aeronautics from across the agency to build a unified approach known as the "NASA Wildland Fire Management Initiative." At least one representative from NASA's Aeronautics Research Mission Directorate (ARMD), Science Mission Directorate (SMD), and Space Technology Mission Directorate (STMD) are involved in this initiative.

To ensure coordinated delivery of mature products, NASA is leading a Wildland Fire Management Industry Working Group (WFIWG). Input from the aerospace and technology industries is instrumental in determining effective and unified approaches. By engaging industry in these efforts early and often, requirements, solutions offered, and evaluation processes are better defined and streamlined.

To better understand the large scope of the wildland fire current state, the inter-agency working group is focusing on six use-cases: prescribed burns, remote sensing, airspace management, communications, logistics, and suppression. The ConOps development team is sequentially addressing each of the use cases by conducting interviews with relevant subject matter experts (SMEs) and conducting literature review. The information gathered from SME interviews and literature review is then summarized in a use case white paper. The white paper is distributed to all contributors prior to a tabletop exercise where the proposed approaches are discussed in detail. The tabletop informs an updated version of the white paper that is published to the public with opportunity for feedback. In addition, the WFIWG is notified of the progress and participants may provide feedback. These white papers, listed in *Section 3 Referenced Documents,* then inform this ConOps. As to date, prescribed burns, remote sensing, and airspace management are the only use cases to have been considered in this interim ConOps.

This is the first version of an iterative ConOps. The ConOps development will continue with more white paper and tabletop cycles to inform future versions. The cycles will slowly build towards collaborative testing and demonstrations.

It is necessary to note there are many other efforts researching possible improvements within the various levels of government, industry, and the international community. This ConOps intends to be a collection of those efforts as well as supplement them within NASA's areas of technical expertise.

3 Referenced Documents

The following documents are referenced in this ConOps as complimentary, separate from the bibliography.

Identification Number	Title	Description	Revision Number/Date
TBD	Prescribed Burns	Whitepaper on Prescribed Burns as a use case in Wildland Fire	V1.0/30 SEPT 2023
TBD	Remote Sensing	Whitepaper on Remote Sensing as a use case in Wildland Fire	V1.0/30 SEPT 2023
TBD	Airspace Management	Whitepaper on Airspace Management as a use case in Wildland Fire	V1.0/30 SEPT 2023
TBD	Technology Roadmap	Timeline with milestones for incorporating new hardware and software into wildland fire operations.	V1.0/30 SEPT 2025
IEEE-1362-1998 (R2007)	Concept of Operations Format Guide	IEEE Guide for Information Technology—System Definition—Concept of Operations (ConOps) Document	5 DEC 2007

4 Current State of Wildland Fire in the U.S.

4.1 Overview

In developing a Concept of Operations (ConOps), it is important to first understand the current state of the issue the ConOps is meant to address. This should include insight into the history of the issue, events and decisions that may have contributed to the current imperative state, and the various governance, programmatic, cultural, natural, and technological factors that should be considered in identifying and closing gaps or in developing plans to leap-frog the traditional pace of change in efforts to promote rapid advancements to meet growing challenges. The following section examines the current state of wildland fire in the U.S., where we came from, how we got here, the imperative for change, and some of the challenges in affecting those changes. Follow-on sections will address the current state of wildland firefighting in the U.S., the identified gaps, and the desired future state.

4.1.1 Wildland Fire as a Natural and Useful Part of the Earth's Ecosystem

Wildland fire has been a natural part of the earth's ecosystem for millions of years, serving as an essential contributor to forest and rangeland health [2], [3]. Wildland fires can clear out dead organic material that hampers both soil and land-dwelling animals from accessing food and nutrients. Left to accumulate unchecked, the growing layers of material can choke out the emergence of new plants [4]. The reproduction of some trees is dependent on fire to free their seeds and provide then with needed access to fertile soil [5].

Historically, humans have also employed fire as a beneficial tool. Farmers have used fire to remove dead organic material from the previous year's crop in preparation for the next season's sowing [6]. It has also been used as a method to replenish the soil with nutrients and destroy invasive weeds and insects. Indigenous people across the globe used fire to clear land for crops, hunt, and manage the land, and reduce the risk of catastrophic future wildland fires [7]. This tradition of "cultural burning" was closely aligned with native peoples' understanding of their inextricable connection to the land. It also aligned with the wildland fire behavior triangle, where fuel, topography, and weather drive the behavioral characteristics of any wildland fire and, of those three factors, fuel is the only one that humans can affect.

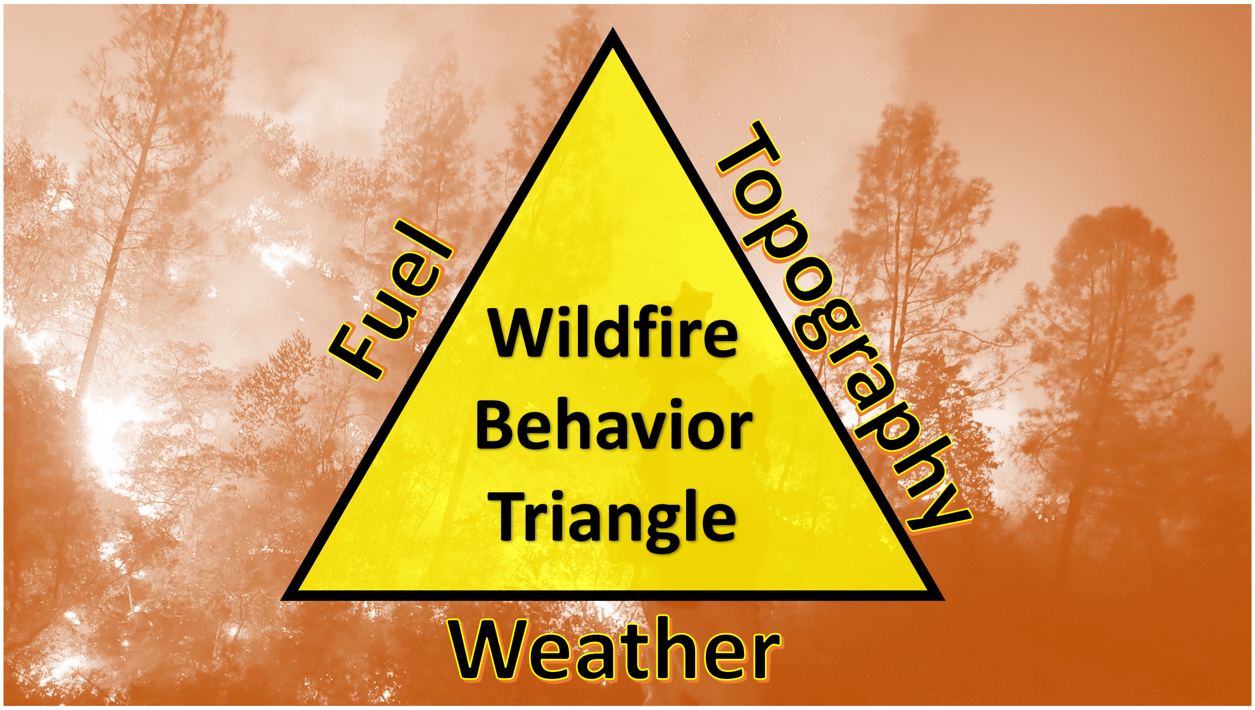


Figure 1. The Wildland Fire Behavior Triangle.

In the 20th century, concepts of "good fire" were largely replaced with public land management practices that put fire on the landscape in a largely negative light. The U.S. Forest Service's (USFS) 10 AM rule of 1935, which mandated that every fire should be suppressed by 10 AM the day after it was first reported was emblematic of this shift in national attitude away from fire as an important and natural part of a healthy ecosystem [8]. While the USFS has since rescinded the 10 AM rule, there is continued pressure to quickly contain and extinguish every wildland fire as soon as possible. Among the contributing factors to this phenomenon are the ubiquitous nature of 24/7 news and video, the powerful still and video cameras we all carry in our smartphones, and the widespread use of social media; wildland fires have become visible nationwide.

Another factor that has continued the pressure on agencies to extinguish wildland fires as soon as possible is a lack of public trust that these fires won't escape the intended bounds placed on them by the agencies fighting them. This can be attributed to notable instances where actively fought, managed, or prescribed fires (which used to be called "controlled" until that term proved to be problematic) broke planned containment, resulting in significant additional acres burned and economic loss. A 2006 USFS report found that only one-third of Americans strongly approved the use of prescribed burns to reduce hazardous fuel loads [9]. This lack of public trust was recently reinforced when a USFS prescribed burn conducted over the winter in New Mexico was allowed to continue smoldering and eventually contributed to the largest wildland fire in New Mexico history, resulting in over 340,000 acres burned, destruction of nearly 900 structures, and the displacement of thousands of people [10]. The continued push of residential communities into the wildland urban interface (WUI) along with an increased understanding of the hazards of wildland fire smoke [11] have also contributed to the public's resistance to prescribed fire as a hazardous fuel reduction method. In some cases, these concerns have led to large scale and lengthy prohibitions on prescribed burning. A notable example of this is the State of Washington that banned prescribed burns on public lands for 18 years due to clean air concerns, only restoring it in 2022 after a notable uptick in wildland fire activity in the State [12].

The combined impact of these policies has been the prolific growth of the biomass on which wildland fires feed. Today, trees in California grow alongside 6–7 times as many trees as there were only a century ago [13]. This densification of forests increased the competition for water and soil nutrients and accelerated drought conditions. The closer proximity of the trees to each other also made them more vulnerable to the spread of disease and pests, weakening the trees and ultimately leading to higher risk for more intense and destructive wildland fires.

4.1.2 Wildland Fire Has Become an Increasingly Destructive and Costly Issue Across the U.S.

In recent decades, as the result of many factors, both human and nature driven, wildland fire has become an increasingly destructive and costly issue. According to the Congressional Research Service (CRS), data compiled by the National Interagency Coordination Center (NICC) indicate the number of acres burned by wildland fire has increased over the past decades [14]. From the 1990's to today, the average annual acreage burned has more than doubled from 3.3 million acres to 7.0 million acres. Since 1960, the top five years with the largest wildland fire acreage burns have all occurred since 2007. Yet while the acreage burned has dramatically increased, the number of wildland fires over the same period has decreased slightly, indicating a growing intensity in wildland fire behavior. This has manifested itself in a growing number of megafires. Megafires are wildland fires that cover more than 100,000 acres (40,00 hectares or 400 square kilometers). Once a rare occurrence, megafires are becoming more frequent. In 1932, the Matilija fire burned 220,000 acres in California. It would remain the largest wildland fire among the west coast States (California, Oregon, Washington) through 2002, but by 2020 it wasn't even in the top 10 of the largest West Coast wildland fires [15]. Likewise, in 2020 Colorado saw all three of their largest wildland fires on record [16]. Of the 1.6 million wildland fires between 2000 and 2022, 254 were megafires, with 16 of those burning over 500,000 acres (5X the definition of a megafire) [14]. While megafires comprise a small percentage of wildland fires, their impact is far greater. Megafires are not just bigger wildland fires, they bring a whole host of negative characteristics that reach far beyond their size alone. Megafires exhibit more extreme characteristics. As illustrated in Figure 2, megafires tend to burn hotter and exhibit more aggressive expansion than traditional wildland fires. In fact, megafires often start in long-unburned areas thick with material piled up on the forest floor, which contributes to these more aggressive characteristics. This intense heat can lead to the decimation of seeds and plant roots that would normally secure the future of a wildland fire scarred area. The extreme heat can also significantly reduce the permeability of the soil, greatly increasing the risk of catastrophic post-fire run off, erosion and landslides. Coupled with the immense burned area left by megafires, these characteristics significantly increase the recovery challenges of megafire scarred landscapes.

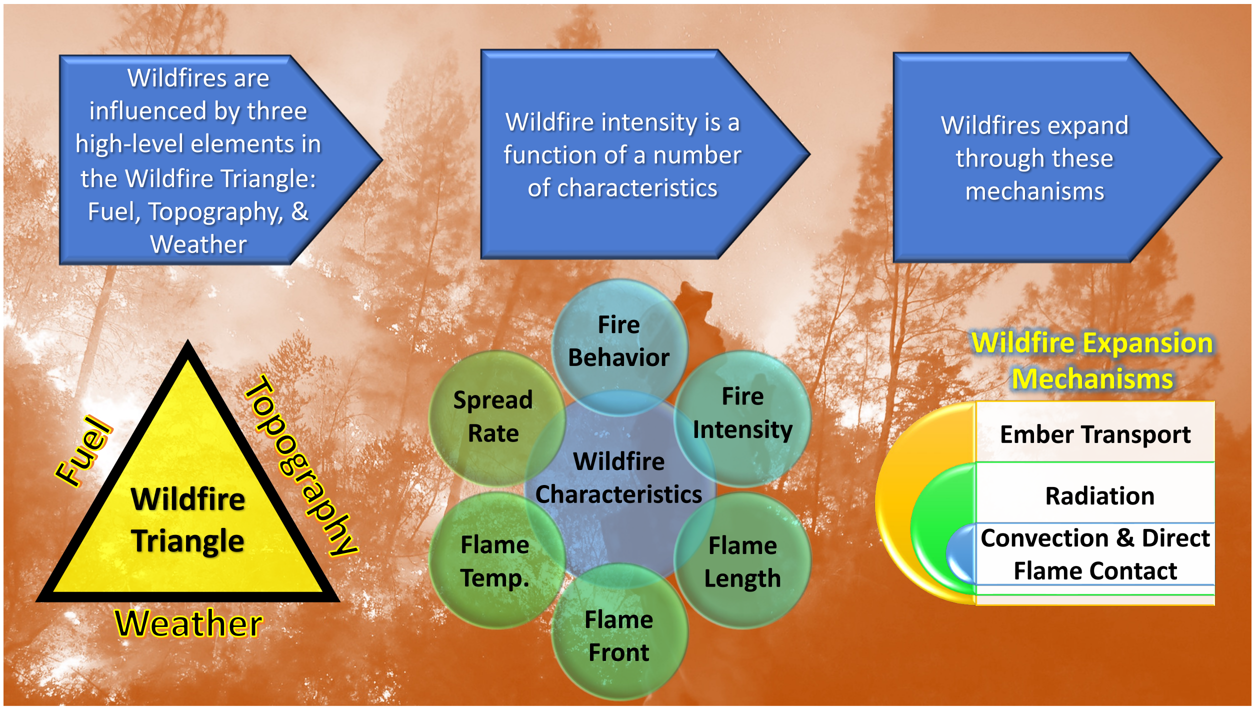


Figure 2. Megafires result in more intense wildland fire characteristics and faster expansion.

Megafires are also emblematic of the growing costs and economic losses present in the current state of wildland fire in the U.S. When the cost of wildland fire is mentioned, most people think of the suppression costs. From 2017–2021 the U.S. Forest Service (USFS) and U.S. Department of the Interior (DOI) spent over $14B in actively suppressing wildland fires, with an average annual expenditure of nearly $2.9B, 21% higher than the prior 10-year average [17].

Yet, the government cost of wildland fire management goes far beyond the suppression activities. Significant resources are expended in preparing personnel, equipment, and infrastructure before each fire year. According to the Congressional Research Service, USFS and DOI were appropriated nearly $620M for preparedness in FY2022 [18]. Following the fire, burned area emergency response (BAER) funding supports emergency stabilization, burned area rehabilitation, and long-term restoration [19]. Together, USFS and DOI post-fire recovery appropriations exceeded $100M. While Federal costs to prepare for, suppress, and recover from wildland fires are significant, it is also important to note that State, Local, Tribal, and Territorial governments also experience similar costs related to wildland fire management.

The cost of wildland fires in the U.S. extends to economic losses and short and long-term health issues. A 2017 report by the U.S. Department of Commerce National Institute of Standards and Technology (NIST) estimated the annualized economic losses as a result of wildland fire to be between $63.5B and $285B [20]. These losses included 12,306 structures burned in 2017, 66% of which were household residences [21]. In 2018, wildland fires in California resulted in $150B in direct and indirect economic losses, with the 2020 fire year resulted in even greater economic costs [22]. These losses are projected to grow. Studies have predicted the number of wildland fires will increase in already vulnerable areas, while at the same time, the number of households present in the wildland urban interface (WUI) continues to grow, placing more homes, businesses, critical infrastructure, and communities at risk [23] [24]. As the number of wildland fires and their attendant losses have increased, so has the burden on governments, businesses, and households. In areas prone to wildland fire, insurance costs have continued to climb, sometimes dramatically [25]. Recently, an even more concerning trend has occurred with two well-known national insurance companies refusing to issue new policies in wildland fire prone areas [26].

Wildland fires also pose significant health risks and costs, not just to those in the immediate vicinity, but also well beyond the confine of the fire itself. Wildland fire smoke is comprised of carbon monoxide, nitrogen oxides, a range of volatile organic compounds, and particulates [27]. Breathing in this mixture can result in a number of immediate effects, including coughing, wheezing, headaches, scratchy throat, shortness of breath, etc. [28]. However, it is the particulate matter in wildland fire smoke that may pose the greatest and most extended health threat. Wildland fire smoke has been found to contain fine particulate matter (below 2.5 microns in diameter, otherwise known as $PM_{2.5}$). What makes particles at this size particularly hazardous is their ability to travel from the lungs into the bloodstream and from there to other organs like the brain. Even in healthy people, exposures to these particles can potentially lead to transient reductions in lung function, and inflammation [29];. They may also impact the body's ability to remove inhaled foreign materials, such as viruses and bacteria, from the lungs, making people more susceptible to infections and diseases. Wildland fire smoke particles have also been found to be more toxic than similarly sized particles found in ambient air [30]. A 1996 Canadian study that include more than two million people and spanned 20 years found exposure to wildland fire smoke was associated with increased incidences of lung cancer and brain tumors [31]. A recent Stanford study also found that wildland fire smoke was worse than smoke from prescribed burns, perhaps because unlike wildland fires, prescribed burns do not consume and generate smoke from burning structures, cars, household items, etc. [32]. Wildland fire smoke and its health impacts have increasingly become a national, regional, and even global issue. As wildland fires burn, the smoke in the immediate area rises with the fire generated heat, often into the stratosphere. There it can be picked up by prevailing upper air currents and/or weather systems and transported thousands of miles from the wildland fire over the course of days or weeks [33]. Once free of the heat generated by the wildland fire and transported to the upper atmosphere, the smoke cools, resulting in it and the fine particles it carries to descend to ground level, far from the fire [34]. Large swaths of the U.S. eastern seaboard and Midwest experienced this phenomenon in 2023 as the result of large Canadian wildland fires [35]. Lasting for days, the smoke not only posed significant health risks, but resulted in major disruptions to outside work operations and leisure activities. What's the potential health cost impact of the growing number and intensity of wildland fires in the U.S.? According to a 2017 study by the Environmental Protection Agency (EPA) that looked at U.S. wildland fires from 2008–2012, the long-term health cost was estimated at $450 billion dollars [36].

4.1.3 Wildland Fire as a Global Issue and its Impact on the U.S.

The previous discussion of wildland fire smoke crossing borders and great distances reminds us that wildland fire is a global issue. According to the United Nations February 2022 Environment Program Report: *Spreading Like Wildland fire, The Rising Threat of Extraordinary Landscape*, the number, intensity, and impact of wildland fires worldwide is predicted to continue to increase, with extreme fires projected to increase by 14% by 2030, 30% by 2030, and 50% by 2100, respectively [37]. That report also estimated the annualized economic burden from wildland fire for the United States to be between $71.1 billion to $347.8 billion (2016 US dollars). To combat this global threat, the UN issued an urgent call to world governments to rethink their approach to wildland firefighting, promoting a new holistic approach that recognizes the important role of landscape management and restoration in wildland fire mitigation. Among those who have adopted this holistic approach is the European Union and their SILVANUS project, which involves 18 countries and 49 industry, government, and academic partners [38]. Like the U.S. approach to wildland fire, SILVANUS has broken it down into three overarching phases, prevention and preparedness (Pre-Fire), detection and response (Active Fire), and restoration and adaption (Post-Fire). As with the current NASA wildland fire management initiatives, SILVANUS includes a high degree of stakeholder engagement in developing integrated solutions that incorporate technology and scientific innovation, environmental, and human factors and validating them through a build-up process of collaboratively developed and executed pilot projects [39].

4.1.4 Wildland Fire in the U.S. (and Globally) is Largely a Human Issue

While the steady rise in the number and intensity of wildland fires has meant significant and growing economic and health impacts to communities, still, wildland fires are largely the result of human activity and therefore within our power to mitigate. A 2017 Proceedings of the National Academy of Sciences (PNAS) research study provided unique insight into the human–wildland fire connection. Evaluating over 1.5 million wildland fires from 1992 to 2012, the study found humans were responsible for 84% of all wildland fires [40]. Figure 3 [41] includes data from 2013 that was not presented in [40].

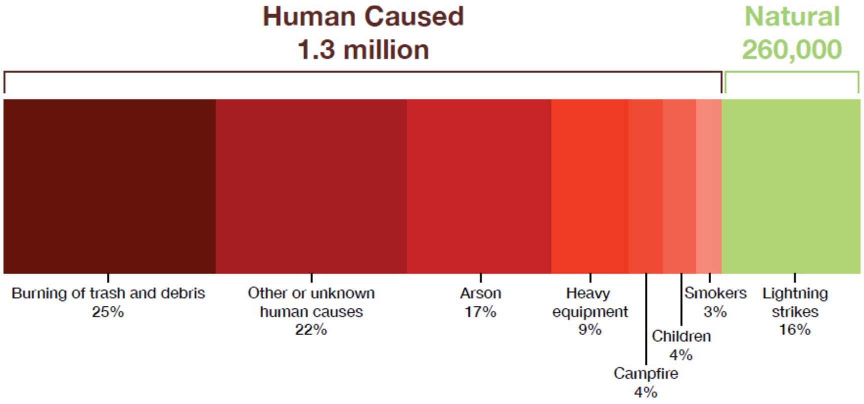


Figure 3. Humans Blamed for Starting Most Wildland fires in the U.S. Credit Climate Central, by John Upton, February 27, 2017 [40] [41].

The study's data and causal determinations were also consistent with data published by the U.S. National Interagency Fire Center (NIFC) [42]. The study also found that human-caused wildland fires were responsible for tripling the fire season length relative to natural (lightning) caused wildland fire seasons, adding an average 40,000 wildland fires annually. As humans are responsible for a large percentage of wildland fire ignitions and the fact that 1 in 6 Americans live in areas with significant wildland fire risk [43], it shouldn't be surprising that humans are also responsible for reporting a large percentage of wildland fires that occur [44]. Given the common human connection between wildland fire causation and reporting, it's only natural that efforts to curb wildland fire ignitions and improve the timeliness and accuracy of wildland fire ignition detections include focused efforts aimed at reducing human caused ignitions while increasing the use of these effective human "remote sensors."

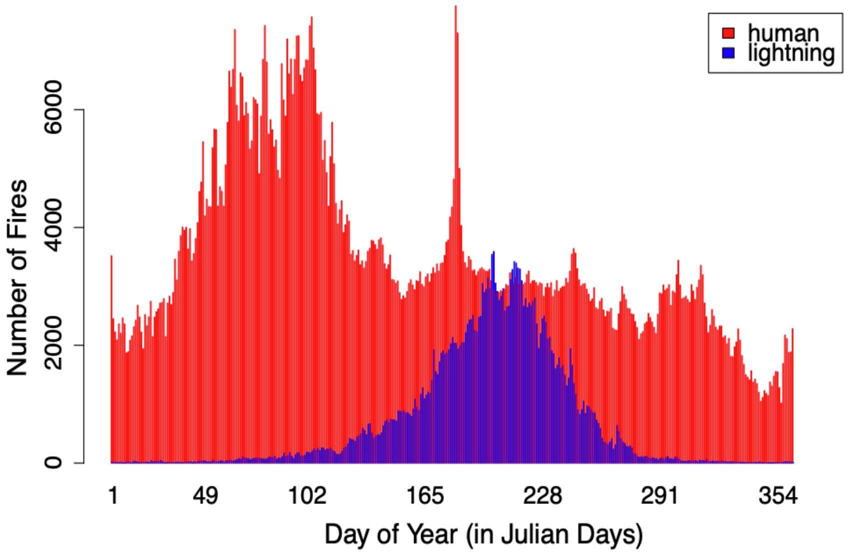


Figure 4. The Tripling of the Fire Year as a Result of Human Ignitions - The Role of People in Current and Future U.S. Fire, Jennifer K. Balch, Dept. of Geography & Earth Lab, University of Colorado Boulder [40].

4.1.5 Wildland Fire and Climate Change

Another contributor to the increase in wildland fires in the U.S. has been the surge in fire weather conditions in fire-prone areas in recent years. As average annual temperatures rise, the vapor pressure deficit, a measure of how hot and dry the air is relative to the soil and vegetation below, increases. This accelerates moisture transfer from plants and soils, increasing the degree and speed at which fuels become increasingly flammable [45]. This phenomenon also reduces the surface water in rivers, lakes, and reservoirs, which serve as important sources of wildland fire suppressant for aerial firefighting aircraft (helicopters and scooper airplanes). Coupled with the historical high incidence of human-caused wildland fire ignitions, this combination sets the stage for increasingly intense wildland fires due to more flammable fuels, occurring earlier in the fire year [46].

4.1.6 Current U.S. Performance in Wildland Fire

Given the increasing number, intensity, economic losses, and costs of wildland fire in the U.S., it is natural to wonder how the U.S. is performing against this growing national threat. The answer is surprisingly unclear. The USFS defines success in the wildland fire response environment as *"safely achieving reasonable objectives with the least firefighter exposure necessary while enhancing stakeholder support for our management efforts* [47]*"*. However, as noted in the latest USFS and DOI Quadrennial Fire Review Final Report, the agencies lack sufficient outcome performance data, with sufficient fidelity and reliability, to inform strategic and programmatic decision making [48]. A good illustration of this challenge is in aerial firefighting, which since its first use in 1930 has grown to one of the largest cost centers in wildland fire management [49]. The USFS 2021 annual aviation report shows the agency spent over $750M on aviation [50]. A companion 2021 USFS report details the 22.8M gallons of retardant expended on wildland fires in the National Forest System lands that year [51]. While output measures like these are consistently tracked and reported, measures of their outcome effectiveness and processes to incorporate them across the wildland fire community remain largely unrealized [52]. These conclusions were reinforced by a 2009 USDA Office of the Inspector General (OIG) audit report and a 2013 GAO review that found there was insufficient information on the performance and effectiveness of firefighting aircraft to directly demonstrate cost-impact and serve as credible planning factors to justify the current and future mix of aerial firefighting aircraft [53], [54]. In response, the USFS initiated the Aerial Firefighting Use and Effectiveness (AFUE) study. AFUE consisted of four modules of experienced firefighters who mapped aerial drop activity from 2015 to 2018, also noting the attendant incident objectives, conditions, and outcomes. While AFUE was able to assess the probability of success of drops based on the collected data, the report (released in 2020) provided no specific plan or requirement to incorporate these planning factors into future aircraft investment decisions or a plan to scale and continue these outcome measurements on future wildland fires [55].

4.1.7 Entities with Wildland Fire Mitigation Roles in the U.S.

Wildland fire, like other natural phenomena, knows no government nor jurisdictional boundaries. Also, as with other emergency response scenarios, effective wildland fire management requires a high degree of responsiveness and dynamic flexibility. Given these facts, it should come as no surprise that a wide range of U.S. agencies and organizations have equity in preparing for and meeting the growing challenge of wildland fire in the U.S.

At the federal level, DOI and the U.S. Department of Agriculture (USDA), through the USFS, lead the nation's wildland fire management efforts. DOI manages the wildland fire response for nearly 500 million acres of national parks, wildlife refuges, preserves, rangelands, and Indian reservations. DOI's wildland fire management program comprises the Office of Wildland Fire (OWF) and four bureaus: (1) the Bureau of Indian Affairs (BIA), (2) the Bureau of Land Management (BLM), (3) the National Park Service (NPS), and (4) the U.S. Fish and Wildlife Service (FWS). In addition, other Interior bureaus and offices (e.g., the U.S. Geological Survey (USGS), the Bureau of Reclamation (BOR), the Office of Aviation Services (OAS)) play an integral role in supporting the program. OWF is the principal office responsible for developing, managing, and overseeing wildland fire management policy, planning, budget, program accountability, and review within DOI. It also serves as the primary liaison office with other agencies like USFS that carry wildland fire responsibilities. USFS carries out wildland fire response across 193 million acres of the National Forest System. The agency also has stewardship responsibilities for over 600 million acres of forestland, including more than 400 million acres of private forestlands [56]. USFS wildland fire prevention and management responsibilities are shared across the National Forest System, State and Private Forestry, and Research and Development Deputy Chiefs and their organizations [57]. DOI and USFS work in close coordination across the full range of wildland fire programmatic responsibilities, including information technology (IT) [58].

DOI and USFS collaborate with a range of other federal agencies on wildland fire prevention, mitigation, and management including:

- Department of Commerce (DOC) (National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS))
- Department of Defense (DOD)
- Department of Health and Human Services (e.g., the Centers for Disease Control and Prevention (CDC) and the Substance Abuse and Mental Health Services Administration (SAMSHA))
- Department of Homeland Security (Federal Emergency Management Agency's (FEMA) U.S. Fire Administration)
- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- Office of Personnel Management (OPM)

While the growing number and intensity of wildland fires in the U.S. is a national issue, its severe effects are decidedly local. Supporting this fact is data from the National Interagency Fire Center, Wildland Open Data source that shows between 2000 and 2019, nearly 2,000 local communities experienced one or more 100+ acre wildland fires within two miles of town [59]. This includes nine major cities with populations in excess of 500,000. The data also indicates that local fire departments provide initial attack response for nearly 80% of all wildland fires [60]. While every State and U.S. Territory experiences a risk of wildland fire, those with the greatest risk have established large, well-funded wildland fire capabilities. Coordination between State and Federal wildland fire agencies is coordinated through the National Association of State Foresters (NASF), whose membership includes representatives from each State, U.S. Territory, and the District of Columbia [61]. Individual State organizations with wildland fire responsibilities work closely with local governments and fire departments to coordinate regional, district, and community wildland fire prevention, mitigation, and management efforts.

With over 70 million acres in recognized Indian land areas spread across dozens of States, Tribal governments also play an important role in wildland fire prevention, mitigation, and management [62]. However, with 574 currently recognized Native American tribes in the U.S., collaboration on wildland fire issues with each tribe would be difficult [63]. As with the States, the tribes collaborate with their federal partners through a formal consortium group. For the tribes, this is the Intertribal Timber Council (ITC) and their Fire Sub-Committee [64].

Given the significant economic impact from wildland fire and the huge sums of government funding that are applied to preventing, mitigating, managing, and recovering from wildland fires, it's also not surprising that private industry, from small companies to large multi-nationals, also has an interest in and desire to assist in meeting the challenges of this national issue. Much of this work is through related industry trade associations.

The complexity of bringing these diverse groups together and effectively and efficiently focusing their efforts to address this complex, dynamic, and growing national issue is no easy task. Varying budget processes and funding levels, governance structures, core mission interests, and operational responsibilities are just a few of the factors that challenge this important collaboration.

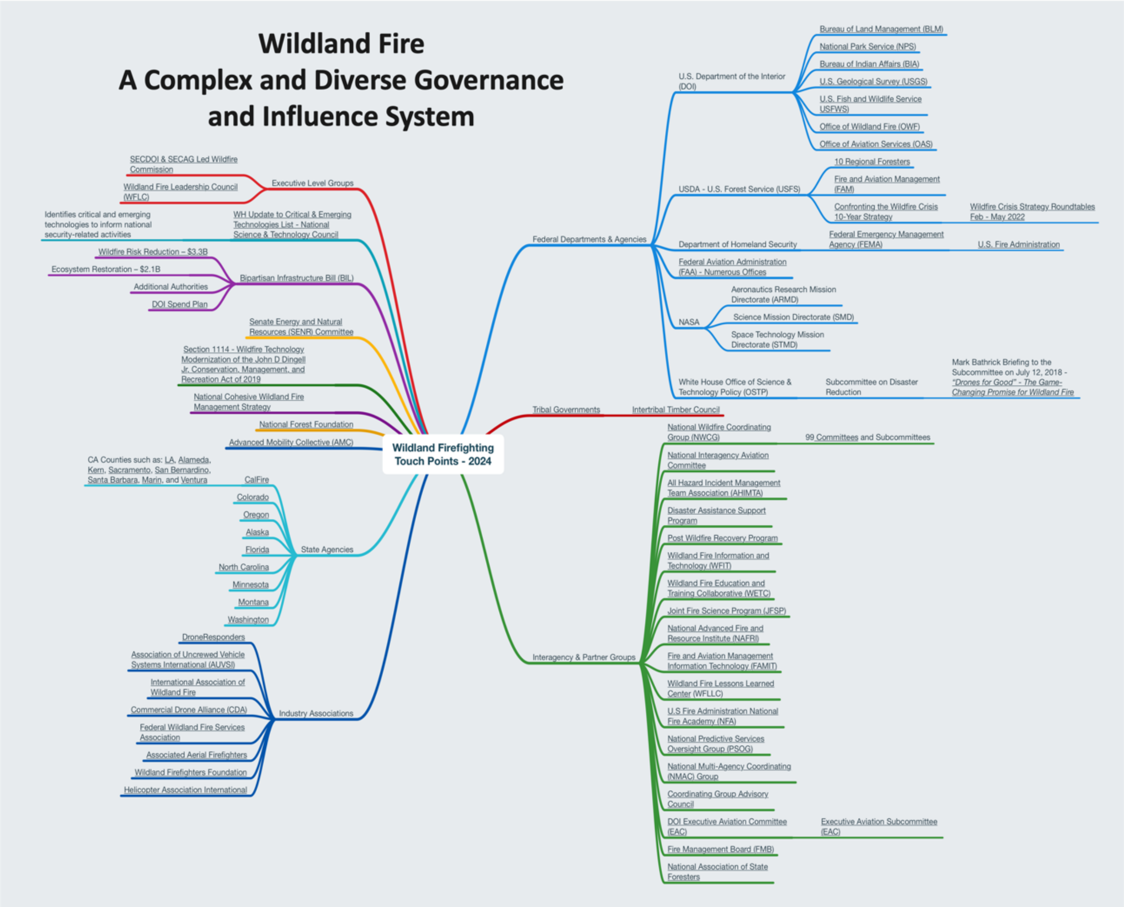


Figure 5. The Complexity of Wildland Fire Governance and Diversity of Its Stakeholders.

In meeting this challenge, the Federal Government and partner agencies have spent considerable effort to develop governance frameworks that support collaboration and standardization across wildland fire in the U.S. At the senior executive level is the Wildland Fire Leadership Council (WFLC). Established in 2002, the WFLC is an intergovernmental organization that is comprised of senior executive federal, tribal, state, and local officials and provides strategic policy application guidance across jurisdictions. Through the WFLC, the National Cohesive Wildland Fire Management Strategy was developed, establishing a national vision for wildland fire management with three national goals: (1) restore and maintain landscapes, (2) promote fire-adapted communities, and (3) improve wildland fire response.

At the senior leadership and operational management levels, the National Wildfire Coordinating Group (NWCG) provides national leadership to develop, maintain, and communicate interagency standards, guidelines, qualifications, training, and other capabilities that enable interoperable operations among federal and non-federal entities. Located at the National Interagency Fire Center (NIFC) in Boise, Idaho, NWCG includes membership from USFS, DOI (and its four bureaus with wildland fire responsibilities), the Department of Defense (DOD), the U.S. Department of Homeland Security's (DHS) Federal Emergency Management Agency (FEMA) U.S. Fire Administration, NASF, ITC, and the International Association of Fire Chiefs [65]. Through its 99 committees and subcommittees, NWCG develops, proposes, and maintains standards, guidelines, training, and certification for interagency wildland fire operations [66]. NWCG publishes and distributes those approved standards through 110 publications that can be found on its public website (https://www.nwcg.gov/publications).

Despite the diligent efforts of the agencies and organizations involved in wildland fire to develop a seamless nationwide approach to wildland fire prevention, mitigation, and management, challenges remain. The details and context of those challenges are reflected in the numerous wildland fire management reports that have been conducted by the U.S. Government Accountability Office (10 reports since 2009) [67]. In addition to efforts by the respective agencies to address the ongoing challenges of integrating such a complex activity across so many agencies, recent high-level initiatives have been put in place to support these efforts.

In December 2021, USDA, DOI and FEMA established a Wildland Fire Mitigation and Management Commission, fulfilling a key provision of the Bipartisan Infrastructure Law (BIL). The Commission will recommend federal policies and strategies to more effectively prevent, mitigate, suppress, and manage wildland fires. It includes federal, state, tribal, county, and municipal governments and non-governmental stakeholders from industry [68]. In January 2023 the Commission issued their first report: Aerial Wildland Firefighting Equipment Strategy [69]. Included in that report were several recommendations for the wildland fire community to improve the availability of technology, including uncrewed aircraft systems (UAS). In one particularly insightful passage the Commission mentioned a passage in the National Interagency Aviation Committee (NIAC) Vision 2027 strategic plan that states ***UAS "may be the first aviation-associated operational innovation for wildland fire management operations in almost fifty years."***

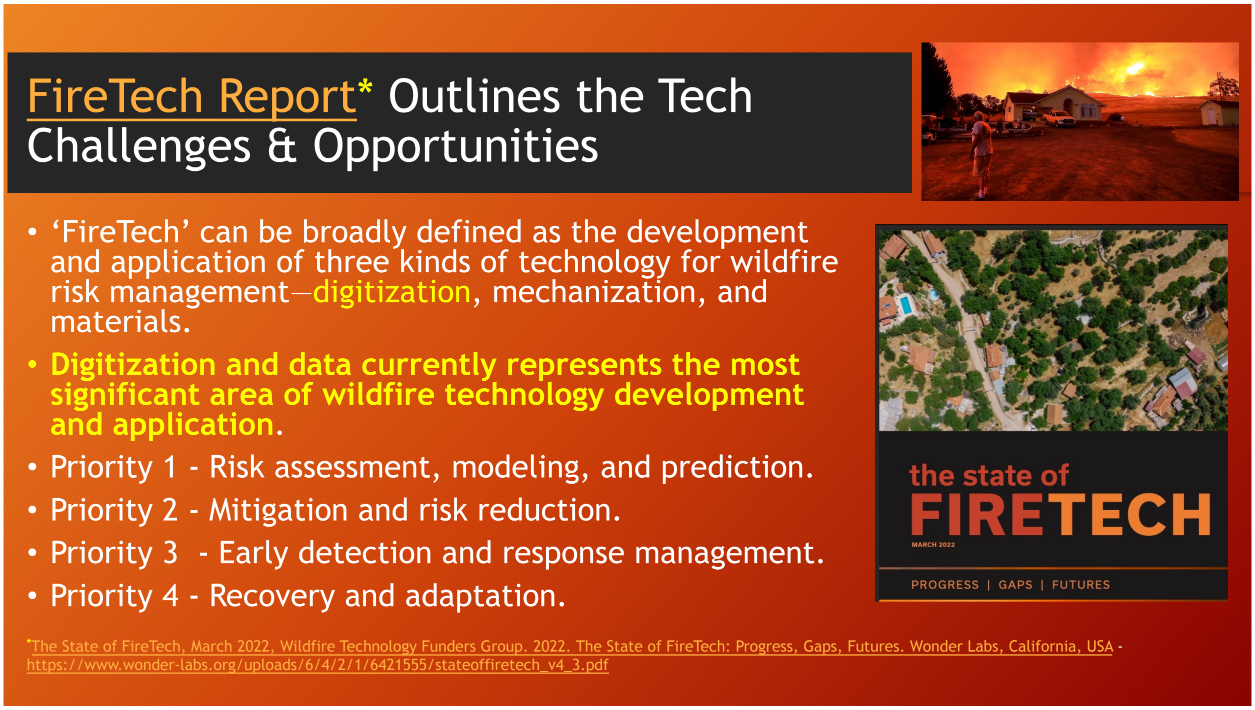
Similarly, on April 22, 2022, the President signed an Executive Order (EO) to strengthen America's forests, boost wildland fire resilience, and combat global deforestation [70]. Specifically focused on advancing a holistic, science-based approach to wildland fire, the EO directed action on data collection and analysis, climate-smart stewardship, and enhanced coordination. In parallel, the President's Council of Advisors on Science and Technology (PCAST) were tasked with providing the President recommendations specific to modernizing wildland firefighting to protect America's firefighters. The PCAST's February 2023 report to the President contained the following five technology-focused recommendations [71]:

- **Recommendation 1:** Given the vulnerabilities and shortfalls in wildland firefighter communications, connectivity, and technology interoperability, immediately assess, adapt, and field currently available technologies.
- **Recommendation 2**: Reverse the current trend of rapidly growing wildland fire suppression costs by establishing a joint-agency executive office (hereafter Joint Office) that can accelerate enterprise-level development and deployment of new technologies that enhance situational awareness and initial attack capabilities.
- **Recommendation 3:** Strengthen the full operational sequence of wildland firefighting—detection, alert, response, and suppression—by assessing existing technologies available within the federal arena, the private sector, and allied nations that could be integrated at each stage.
- **Recommendation 4**: Accelerate improvement of predictive wildland fire modeling tools by expanding research community access to archived satellite data from defense and other government sources.
- **Recommendation 5**: Expand our nation's wildland fire response capacity by encouraging development and field demonstration of prototype autonomous detection, assessment, and containment systems for wildland fire.

4.1.8 Technology's Role in Wildland Firefighting in the U.S.

By its nature, wildland firefighting is a hazardous, highly dynamic, and labor-intensive endeavor. Wildland fires can occur with little to no warning. While hazard assessments can highlight the areas of greatest risk for wildland fire, the exact location of where a wildland fire will occur is unknown until it happens. These factors force wildland firefighters to constantly adapt to new and unfamiliar locations and terrain. Wildland fire characteristics and intensity are largely determined by the three elements of the wildland fire triangle: Fuel, Weather, and Topography (Figure 1). These characteristics also affect the strategy, planning and progress toward containing and extinguishing wildland fires. In the end, those objectives are accomplished by firefighters on the ground. While aerial-delivered suppressant can reduce the ferocity and amount of fire facing firefighters on the ground and retardant lines can help slow or contain the spread of wildland fire, it is the firefighters on the ground who conduct the manual actions to ensure the wildland fire is contained and then extinguished. It is these everyday life and death factors and ultimate responsibility for containing and extinguishing the fire in protecting the communities they serve that has colored wildland firefighting's approach to technology adoption for the last 150 years.

The factors described above have contributed to the wildland firefighting community's lagging in identifying, developing, integrating, and adopting new/currently available technologies that could save lives, time, and money. In their February 2023 Report to the President – Modernizing Wildland Firefighting to Protect our Firefighters, the President's Council of Advisors on Science and Technology specifically noted that ***"critical aspects of wildland fire response that are stuck—technologically and organizationally—in the last century*** [72]***."*** Similarly, a 2022 State of FireTech report by the Wildland fire Technology Funders Group found that current wildland fire technology consistently lagged behind other government operations in materials, mechanization, data, and digitization [73].



FireTech Report* Outlines the Tech Challenges & Opportunities

- 'FireTech' can be broadly defined as the development and application of three kinds of technology for wildfire risk management—digitization, mechanization, and materials.
- **Digitization and data currently represents the most significant area of wildfire technology development and application.**
- Priority 1 - Risk assessment, modeling, and prediction.
- Priority 2 - Mitigation and risk reduction.
- Priority 3 - Early detection and response management.
- Priority 4 - Recovery and adaptation.

*The State of FireTech, March 2022, Wildfire Technology Funders Group. 2022. The State of FireTech: Progress, Gaps, Futures. Wonder Labs, California, USA - https://www.wonder-labs.org/uploads/6/4/2/1/6421555/stateoffiretech_v4_3.pdf

Figure 6. The State of FireTech Report, March 2022.

Also, in its January 2023 initial report (Aerial Equipment Strategy), the congressionally directed Wildland Fire Mitigation and Management Commission noted the rarity of technological progress in aerial firefighting, including this comment on page 56 of the report: ***UAS "may be the first aviation-associated operational innovation for wildland fire management operations in almost fifty years."***

The lagging adoption of technology has also made it difficult for the wildland fire community to collect important quantitative outcome measures that would be essential in developing the planning factors necessary to develop and justify current and future aerial firefighting requirements. Several reviews and reports by the Government Accountability Office (GAO) have pointed this out [74].

The need for direction and funding for wildland fire technology has not gone unnoticed by Congress nor the Executive Branch. The John D. Dingell Jr. Conservation, Management and Recreation Act of 2019 [75] required USFS and DOI to implement technologies to:

- Use technology to track fire resources
- Provide situational awareness through mapping
- Display resources on an active and accessible map
- Provide an accurate picture of the post-fire landscape to prevent flooding, erosion, etc.
- Enable information gained in past fires to predict the likelihood of future wildland fires

It also required USDA and DOI to ***"establish a research, development, and testing program to assess unmanned aircraft system technologies, including optionally piloted aircraft, across the full range of wildland fire***

operations [76].” However, many of these requirements, including some with mandated 2021 completions remain unmet.

More recently, the Bipartisan Infrastructure Law (BIL), the Infrastructure Investment and Jobs Act (IIJA), and the Inflation Reduction Act (IRA) each included investments in wildland fire technology and equipment as well as funding for other firefighting priorities. The BIL provided $8.25B for investments in wildland fire management including enhanced wildland fire detection and risk reduction [77].

Wildfire Funding Reflects National Urgency

- **$8.25B in the Bipartisan Infrastructure Law for a suite of programs aimed at reducing wildfire risks, detecting wildfires, instituting firefighter workforce reforms, and building more resilient infrastructure.**
  - **$878M to** improve ecosystem health and remove fuel for wildfires.
  - **$325M for** burned area restoration activities.
  - **$164M** to improve firefighter compensation, benefits, mental health resources, and training.
  - **$72M to** improve the use of technology and equipment to detect and respond to wildfires.
  - **$10M** in the Joint Fire Science Program to identify and fund high-priority fire science research.
- **$24B** in the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA), distributed over 40 different programs administered by a dozen agencies.

Figure 7. Bipartisan Infrastructure Law Funding for Wildland fire Technology and Improvements.

Together, the IIJA and IRA provide $24 billion in funding for wildland fire issues, distributed over 40 different programs and administered by a dozen agencies [78].

However, despite these many efforts, the development, testing, adoption, and integration of new technology in wildland fire is spotty and, as a whole, continues to lag that of other critical public service and emergency response areas. Notable successes in implementing new technologies in wildland fire include the introduction of the very large airtanker (VLAT), the move away from vintage military aircraft to modern NextGen airtankers, the development of the amphibious single engine airtanker (FireBoss), and the development of a first-of-its-kind 24/7 UAS-based aerial ignition capability for prescribed burns, back burns, and burnout operations. Additional discussion on the factors that contributed to these successful new technology adoptions can be found in *Section 5 Future State* in this ConOps.

4.1.9 Conclusions

Widely available data on the increasing number and intensity of wildland fires in the U.S. confirms that the current state of wildland fire in the U.S. is more perilous than at any time in our history. This increased and growing wildland fire activity threatens the safety, health, and economic prosperity of all Americans, not just those who live in fire-prone locations. As we have recently experienced, wildland fire is a growing global issue that can threaten Americans through the economic, health, and safety effects of wildland fire smoke that can travel thousands of miles and linger over vast areas for days.

Wildland fire prevention, mitigation, management, and recovery processes have largely remained the same for decades, mostly absent of the numerous technology improvements that we have experienced and have come to rely on in our everyday lives. With recent improvements in firefighter pay, technology has been widely identified as the most significant opportunity to improve the safety of those firefighters by giving them access to the many modern technologies and related tools that have become commonplace in other government and industrial applications. Successfully overcoming the traditional barriers that have resulted in *critical aspects of wildland fire response being* *stuck—technologically and organizationally—in the last century will require new thinking and new approaches, similar to those used by a few notable wildland fire technology introduction success stories.*

4.2 Current State of Wildland Fire Mitigation & Operations in the U.S.

There is no generalized national standard for wildland fire prevention, fighting, and recovery, but there are well documented suggestions for procedures. Federal land managing organizations refer to the NWCG's well documented guidelines for procedure, equipment, and training.

4.2.1 Wildland Fire Mitigation as a System

Wildland fires are not confined to sterile, controlled environments, away from everyday life. Each time a fire breaks out, many different entities and routines are disrupted or stopped until the fire is extinguished. The largest stakeholders of which are the owners, tenants, and travelers of both land and aerial infrastructure–already inherently complex systems. In this sense, mitigation of wildland fires involves any entity that might encounter or have a stake in these arenas, whether private or public. For example, a prescribed burn may need to take place simultaneously on a section of private farming property and a section of Bureau of Land Management (BLM) land or span across a state highway. Likewise, a larger fire incident may warrant a temporary flight restriction (TFR) in the airspace around the fire, which prohibits general and commercial aviation from flying through that region [79]. Both scenarios affect people and operations that are completely removed from the fire in both responsibility and stake in the aftermath. Therefore, unlike most technical concepts that develop and mature in their own colloquial silo, this wildland fire concept of operations takes on a "system of systems" approach–with each aspect or component affecting the others around it. While locally, different parts of the system may manifest in different forms, the key idea of this ConOps is to align the overall system in a cohesive way so that there is a homogeneity to the broader, wildland firefighting mission. This "holistic" approach ensures a certain robustness where if one component becomes weakened or fails, the entire system remains capable [80].

4.2.2 The Three Phases of Wildland Fire Mitigation and the 7 Links of the Wildland Fire Chain

This report categorizes the large wealth of tools, procedures, responsibilities, and standards that make up wildland firefighting into three phases: Pre-Fire, Active Fire, and Post-Fire. Note, however, there is currently no national common operating picture (COP) for any of these phases, which are simply an organizational tool for the sake of clarity in this ConOps.

TABLE I
THREE PHASES AND SEVEN LINKS OF WILDLAND FIRES

Pre-Fire		
Pre-Year Assessment	**Risk Mitigation**	**Dynamic Risk Assessment**
Previous year's activities' effectiveness Resource allocation and funding	Fuel reduction Personnel training Equipment readiness Systems and processes checks Infrastructure resiliency Community resiliency Public service announcments	Fuel flammability levels Weather prediction Red flag warnings
Active Fire		
Ignition Detection	**Initial Attack**	**Extended Attack**
Utility fault monitors EO/IR cameras Satellites Lightning detection 911 and bystander reporting	Ground and aerial crews Strategic placement of assets Area of operation	Increased complexity Resource prioritization Degraded visual environments Logisitics Emergency extraction
Post Fire		
Recovery		
Emergency stabilization Erosion and flood control Reforestation and rehabilitation		

Within the three phases, there are seven sub-phases that describe the activities performed. These seven "links" are referred to as the "wildland fire chain." "Pre-Fire" can be thought of as any activity that will aid in the efforts during later phases through anticipation or prediction of the needs of the coming fire season and being proactive in addressing those needs when possible. "Active fire," as the name suggests, includes any activity that works to address specific incidents in real time, as they arise. Finally, "Post-Fire" includes all activities that aid in the clean-up, incident assessment, and maintenance after a fire occurs. Table I depicts the links that are associated with the three phases, along with examples, not exhaustive, of activities within each of the links.

Importantly, the chain is also cyclical; there is a potential to see a feedback loop, either positive or negative, without intervention within the chain. For example, if the pre-year assessment of fuels or climate prediction is lacking, the Active and Post -Fire phases are going to be exponentially more challenging in the coming cycles. In fact, this is widely accepted as the main reason California has seen worsened fire seasons: until recently, wildland firefighting focused solely on the active fire phase, not accounting for a changing climate with un-mitigated and growing fuel [81]. Using that same idea, the introduction of a new technology, standard, or procedure to increase the efficiency and safety in one link could significantly reduce the resources spent across the entire chain. Through multiple cycles, incremental improvements would also compound to have large-scale, measurable impacts.

4.2.3 Technology Gaps and Limitations

Each of these activities exist in a trade space between what is technically possible and what is available to first responders, and in recent years the size and frequency of wildland fires has begun to out-pace the technological maturation of the tools available. Defining the limitations and challenges in those trade spaces is critical to closing the gaps in the current state of the art and setting the foundation for further technical advancement.

Common themes across all current limitations are scope, sophistication, and fidelity of the available tools, whereby improvements in these areas become ambiguous due to a lack of standards that would ensure the overall mission objectives of first responders remains intact and attainable. Additionally, policies within and surrounding the wildland firefighting mission add areas of regulation and define boundaries that current systems must obey. This includes, but is not limited to, ownership of land, ownership of data, FAA airspace and airworthiness criteria, environmental regulations, personnel shift requirements and safety, and public notice and access to information. This leads to the current state sticking to proven methods that meet mission objectives, with minimal or slow progression towards new tools.

TABLE II
TECHNOLOGY GAPS AND LIMITATIONS

		Area of Limitation or Technical Gap			
		Scope & Adoption	Fidelity & Sophistication	Latency or Efficiency	Management or Standardization
Chain Phase	Pre-Fire-Year Review and Risk Assessment	X	X		
	Pre-Fire Active Mitigation	X			X
	Dynamic Pre-Fire Risk Assessment	X	X		
	Timely Ignition Detection	X	X	X	
	Rapid Initial Attack				
	Extended Attack	X	X		
	Post-Fire Recovery	X	X		X

4.2.4 Current Operations Structure

4.2.4.1 Current Operations Structure Overview

As mentioned in *Section 4.1 Overview*, there are many government agencies and local entities that take on large portions of the wildland firefighting arena or otherwise aid in mitigation efforts. While the larger players—such as CalFire, US Department of the Interior, US Department of Agriculture's US Forest Service, and Tribal governments—span all three phases of the wildland fire chain, others contribute in specific, yet critical ways. The National Oceanic and Atmospheric Administration (NOAA), for example, provides real-time weather prediction and information during a fire incident with an assigned Incident Meteorologist (IMET) employed onsite [82].

Additionally, there are several unifying entities consisting of interagency and partner groups, which are membership-based committees that create common practices, news, tools, and resources for the community. One such example is the National Wildfire Coordinating Group (NWCG), whose mission is to act as a leadership entity that enables interoperability across the various agencies and stakeholders by outlining many best practices through its creation of proposed goals, requirements, and standards to increase safety and efficiency [83]. Importantly, however, these standards are not mandated or enforced, and purely serve as guidelines to participating members.

Although these unifying groups exist, and the agencies within the wildland firefighting sphere are numerous, there is no official or national hierarchal structure. Each agency adopts its own mission, resource acquisitions, headquarters and satellite bases, and staffing based on their individualized needs and internal predictions. Likewise, publicly available federal agency data is seldom collocated nor widely shared and is often in formats not readily utilized [84]. This lack of a final arbiter allows ambiguities to compound until they complicate or hinder response efforts and technical progress, manifested in the following ways:

- Responsibility Devolution – when all share equal responsibility, no one is responsible. Can result in either stagnated or duplicated efforts.
    - Example 1: pursuit of products or deliverables are either inconsistent or non-existent due to a lack of enforcement or existence of standards against which to conduct verification or validation.
    - Example 2: two different agencies unknowingly attempt to research and create a product that address the same need, essentially using twice as much funding to create one product.
- Responsibility Fabrication – Arbitrary rules are put in place to maintain power or money. Often leads to inefficiencies or miscommunication.
    - Example: when differing jurisdictions attempt to collaborate, a local agency may bar outside agencies from assisting due to disagreements in mission planning or training, which can obfuscate response efforts.
- Uninformed Responsibility – Without clear guidelines or collaboration, decisions may be made for the sake of making progress, without justification. Often leads to unsafe or mis-managed operations.
    - Example: In a worsening situation with resources spread thin, an agency might O.K. the use of outdated equipment, not realizing the engineering justification behind its intended lifecycle and potentially leading to catastrophic failure.

Unfortunately, all three can occur at one time, especially when a lack of regulation has been the precedent. For the last few decades, it has been common practice to recycle retired military aircraft for use in fighting wildland fires. This has led to many firefighting aircraft operating well past their intended lifecycle and structural fatigue limits. In 2015, Department of the Interior and US Forest Service representatives in Montana discovered that a few UH-1 Huey helicopters under their oversight had been significantly modified with alternative components that did not comply with safety recommendations outlined by the NWCG. Ultimately, they made the difficult decision to ground the helicopters over safety concerns. However, due to the precedent, this was incredibly controversial amid an intense fire season, and led to scathing articles regarding the decision. For this situation, responsibility fell on the entire community to maintain airworthiness standards, and over time, those standards were flexed and expanded in such a widespread way, that it reached unsafe levels. Had there been any regular enforcement of airworthiness standards, the pressure to fly would have been mitigated through justifiable means.

While hierarchal structure is not a novel concept for federal agencies, it has only recently begun to gain traction for wildland fires due to the newfound attention they have received in the last few years. In a 2023 report to the president of the United States, the President's Council of Advisors on Science and Technology (PCAST) recommended creating a new joint executive office with Cabinet-delegated authorities to implement a unified science and technology strategy for wildland fires, similar to the joint strategies that have been achieved for national defense, noting that "…no single entity has successfully marshaled the diverse expertise needed across multiple agencies to address this extremely complex challenge with focus and persistence" [1].

The three specific case studies, or "use cases," were chosen to better understand the tools and processes currently available to the agencies involved in fighting wildland fire, with the aim of uncovering common themes or areas of improvement. These use cases were prescribed burns, remote sensing, and airspace management, all of which touch on the Pre-Fire, Active Fire, and Post-Fire phases. For detailed information of these use cases, please refer to each respective publication in *Section 3 Referenced Documents*. There are also plans to investigate three additional use cases of communications, logistics, and suppression next fiscal year.

4.2.4.2 Current Operations Description

This ConOps organizes wildland fire response tactics into seven chronological, cyclical links, known as the "wildland fire chain," as summarized in *Section 4.2.1 Wildland Fire Mitigation as a System*. Each phase contributes critical activities to the overall mission, as outlined below for the current state-of-the-art.

4.2.5 Pre-Fire Phase

4.2.5.1 Previous Year Effectiveness Metrics

Before any agencies begin efforts towards the upcoming fire season, there is typically an assessment of the previous season to help agencies track trends, inform quantitative predictions for the upcoming year, and glean insight into the quality of response they provide to the community. Historically, this has typically occurred in the Winter and early Spring months of the calendar year; however, with the continuous nature of recent fire seasons, this can be a year-round effort.

Currently, one of the more general methods of incident data collection is the US Fire Association's National Fire Incident Reporting System (NFIRS). NFIRS is a voluntary data collection software and database that is all-encompassing for incidents related to fire, with sub-modules extending to hazmat, emergency medical services (EMS), casualties, arson, structure fires, and wildland fires. This data then is collected within FEMA's OpenFEMA API [85]. In the case of a wildland fire, the user would fill out both the basic and wildland fire modules, as well as the modules for apparatuses and personnel if the user determines more information is needed. If any personnel are killed or injured, the casualty and/or EMS modules are also filled out.

TABLE III
NFIRS 5.0 DATA COLLECTION FOR WILDLAND FIRE [86]

NFIRS 5.0 Data collection for Wildland fire [86]	
Basic Module	
• Fire Department Identifier • Location • Incident Type • Aid Given or Received • Dates And Times/Shifts/Special Studies • Actions Taken	• Dollar Losses And Values • Casualties • Hazmat Releases • Property Use • Persons and Entities Involved
Wildland Fire Module	
• Property details • Fire cause • Ignition information • Fire suppression and management • Mobile property type • Equipment involved in ignition	• Weather data • Fuel model at origin • Total acres burned • Property management • Person responsible • Fire behavior
Apparatus and Personnel Modules	
• Apparatus identification and type • Dispatch, arrival, clear dates, and times • Number of personnel, ID, & Rank	• Use • Actions taken

The best way for agencies to assess their effectiveness, however, is to conduct internal reviews on specific methodologies within the agency. NIFC outlines several types of reviews that may be conducted in their standards of operations, but most applicable to the previous year effectiveness are significant wildland fire reviews (DOI only); continuous improvement assessments (USFS only); individual fire reviews; declared wildland fire reviews; as well as general lessons learned and after-action reports [87].

An individual fire review is the general review process for any fire in the United States that does not meet criteria for a significant fire review, including prescribed burns. According to the DOI's interagency standards, these reviews evaluate decisions and strategies, correct deficiencies, identify new or improved procedures, techniques, or tactics, determine cost-effectiveness, and compile and develop information to improve local, state/regional, or national fire management programs. An individual fire review will be considered for any fire larger than 50,000 acres, or if the fire is deemed of significant social or economic impacts.

A significant wildland fire review takes place for any fire that accumulates over $15 million in suppression costs, and at least 50% of it occurs on Department of the Interior land. Once these thresholds are reached, the review can begin, ideally when the incident management team is still in place immediately following the fire. For fires spanning multiple agencies, the lead bureau is decided on by all the groups involved.

Continuous improvement assessments act as a "catch-all" for any incident that may need or benefit from a review at the federal level due to their complexity and national significance. Incidents would be selected for this type of assessment if they accurately capture a wide scope of the community at large or are multi-agency in nature. Additionally, the goal of these reviews is not to find faults, but rather increase the overall knowledge of the trade for better tactics in the future. This is further documented in the Forest Service Manual (FSM) section 5139 [88].

Declared Wildland fire Reviews focus specifically on prescribed burns, here called a "declared" fire. Every prescribed burn must conduct an assessment of the outcome, as noted in PMS 484 [89].

Lessons-learned reviews are to be conducted whenever there are specific, unintended outcomes or near-misses. These are not punitive in nature, nor do they replace serious accident investigations, but are rather educational opportunities intended to prevent the incident from happening again. These reviews have a third-party facilitator and bring in subject matter experts to provide analyses on a root cause as well as recommendations. All lessons learned reports are collected at the Wildland fire Lessons Learned Center [90].

4.2.5.2 What is Lacking

There is much room for improvement in pre-season assessment from a firefighting science perspective. Currently, there is simply a lack of empirical metrics to guarantee comparative data collection across the spatially and temporally dynamic nature of wildland fires: since so many factors in both the space and time domains impact the result of a response effort, the same approach may not work twice [91]. While the NFIRS database is a powerful tool, it is currently used mostly for reporting and high-level statistics, rather than specific-incident analyses. Additionally, it is such a large database, and the format is not easily accessible for the average person, so knowledge of accessing FEMA's application programming interface (API) is required [92]. Likewise, internal reviews can only get as detailed as the data collected, such as total acres burned and total suppression cost. While these are good data points, they don't indicate if the response was efficient, or even optimal. Furthermore, many fires do not get reviewed, as they simply are not required to be under the niche attributes that trigger a review [93].

[Tools and Data - Forest Inventory and Analysis National Program (usda.gov)] [Forest Service Research Data Archive (usda.gov)] [Tools & Products | US Forest Service (usda.gov)]

4.2.5.3 Active Pre-Year Risk Mitigation

Another component of the pre-season phase is risk mitigation. This incorporates fuel reduction, personnel and equipment training and readiness (including systems checks), infrastructure resiliency measures, and public service announcements. All of these proactive measures aim to reduce the impact of any potential fire, should one occur, and increase the probability of containment. In addition to the active fire attack phases, this is perhaps one of the most developed areas in the wildland firefighting discipline, with countless resources available on the USFS and NIFC websites.

4.2.5.3.1 Fuel Reduction

The United States Department of Agriculture (USDA) and state strategists have identified prescribed burns as a valuable tool for building forest resiliency, noting that prescribed burns are effective in hazardous fuel reduction and are resource efficient. These strategy groups, such as California's Wildland fire and Forest Resilience Task Force, have set goals to treat additional acreage with prescribed burns to expand fire-management efforts. California aims to treat an additional 50 million acres in the next 10 years, and the Florida Forest Service, The Nature Conservancy, and the Natural Resources Conservation Service are all conducting annual reviews to ensure the amount of acreage treated is increasing.

Each prescribed burn is unique in its purpose and process, thus requiring coordinators to understand the situationally required procedures. Although national standards outline coordination structures and training requirements, each state, district, and county can adapt its approach within its jurisdiction to meet local needs. For example, there are often variations in required permits, smoke-management planning, environmental restrictions, and whom to notify when preparing for a prescribed burn.

While approval and planning of a prescribed burn spans anywhere from 6–12 months, most of this effort focuses on the "day-of" and ensuring the prescribed burn is conducted safely and efficiently. A key component of this is the creation of a "burn plan," which is an all-encompassing document that includes any information necessary for a safe and effective burn, such as approvals, procedures, go-no-go criteria, etc., and is handed out to all personnel involved. Some modeling and fuel predictions help inform ignition points and mitigate the risk of uncontrolled spreads, although these models lack the fidelity to fully rely on them and planning deliberately accounts for large margins of error.

Most prescribed burns rely on ground-based ignitions: torch fuel, drip torches, flares, fuses, gel fuel blivets, propane torches, and terra torches, etc. [94]. PMS 443 details the requirements for equipment use, training, fueling, inspection, maintenance, storage, and transport [95]. Aerial ignition is not a typical ignition tool among prescribed-burn practitioners, but most necessary in remote areas where ground crews struggle to ignite by hand and is typically performed by federal agencies on public lands. Further, aerial ignitions are performed more frequently by helicopters as opposed to UAS. A list of standard equipment can be found in PMS 501 [96].

Aerial operations often rely on iPads with ForeFlight to deconflict the airspace and pilots will work with their coordinators to pass along relevant information [97]. For UAS operations, operators will send out a Notice to Air Missions (NOTAM) to communicate the operations to GA. This caution is a general notice, not a restriction. Besides NOTAMs, there is no way to deter non-participating airspace users from encroaching on operations. The current state of airspace management procedures for prescribed burns does not support larger UAS operations, as there is no larger system outside of the pilots on the ground operating. Furthermore, pilots deconflict using only visual line of sight and auditory clues, which limits their ability to manage more intensive airspace.

However, UAS are not reaching their full potential in the wildland fire use case because of their limited capabilities and lack of community support. UAS manufacturers do not currently design with wildland-fire use cases in mind. These systems often perform well for casual applications and in simple operational environments (e.g., non-rugged terrain); however, prescribed burn operations require enhanced performance (e.g., extended battery life, additional sensors, built using resilient materials). Technological development in these areas would make UAS more suitable for firefighting and reduce the time spent traveling between launch and recovery zones (LRZs).

Prescribed burns carry some risk, which makes it imperative that all tools, including remote sensing devices, are brought to bear. The process of gaining approval for a prescribed burn can be arduous, in part because many members of the public are opposed to them for a variety of reasons, even though a prescribed burn can lower the risk of a more destructive fire. Programs to educate the public about how fires can be monitored and safely controlled would help in this matter.

Data obtained from remote sensors can provide important information about what was happening before a fire broke out that can lead to insights into how things could be handled better in the future. For example, what conditions made the occurrence of fire more likely? What could be done the next time to have a better response to such a fire? Can we identify areas where a controlled burn might have been helpful in decreasing the risk of a major fire can be valuable. What are the best ways of using existing remote sensing devices, and what improvements in technology could lead to better results?

Regardless of the method of ignition, ground crew personnel measure conditions around the burn unit. Standard instruments to measure fuel and humidity include sling psychrometers and fuel sticks. A Kestrel Weather Meter may also be used to monitor wind speed, gusts, average wind, temperature, and humidity. Once collected, this information is then relayed from the ground crew to the Burn Boss over handheld radio.

4.2.5.3.2 Personnel Training and Equipment Readiness

There are a several categories in which training material is offered for all types of firefighting personnel. There is management, leadership, and command; finance; logistics and planning; dispatch; aviation; investigation; preparedness and prescribed burns; and operations. Over 700 different courses are available as virtual and in-person instructor-led courses, or via online self-learning modules through the NWCG training center, the interagency learning portal, or FEMA [98] [99] [100].

For specific roles, the USFS outlines minimum requirements by position through the Interagency Fire Program Management Standards (IFPM) [101]. Further details for specific positions are outlined in the NWCG position catalogue and the Forest Service and Aviation qualifications guide [102] [103]. If a candidate meets these requirements, they have the chance to be part of its apprentice program. Here, individuals are paid to shadow specific positions as they receive on-the-job training totaling 3,000 hours [104]. Once fully-integrated into a role, each position must stay current with annual refresher courses and exams, with some roles – such as pilots – requiring cognitive and physical exams. In California, the Statewide Training and Education Advisory Committee (STEAC) meets quarterly to revise and update training to reflect the current environment [105].

Each year in the late Spring and early Summer, fire agencies officially declare fire season. Among other things, this signifies the start of peak staffing and equipment allocation, including seasonal roles. Perhaps one of the most impactful forms of training in this regard are annual academies and interagency collaborative exercises ahead of the official season. One such example was an event held near Sacramento, CA in 2023, where teams from both CalFire and the California guard held joint exercises in anticipation of the upcoming fire season [106]. Over a multi-day period, the group practiced tactical maneuvers and aerial drop communications in a low-risk environment with the newest equipment and staff, with the objective of forming the interagency bonds needed for a successful mission. Similar events are held all over the country, such as Colorado and Washington [107] [108].

When it comes to equipment, the NWCG PMS 448 and 449 are very thorough repositories for what kind of small equipment is available to agencies, providing high-level instructions for how to maintain and store them, or purchase a replacement. This includes personal protective equipment (PPE), aviation, clothing and cordura, camping, medical and other kits, fuel handling, water handling, and miscellaneous tools [109] [110]. Many of these smaller tools and equipment have usage trainings associated with specific positions that require them, and typically have their own training module, such as NWCG's S-130-8 [111] [112].

Large machinery and equipment such as land or aerial vehicles require a different approach, of course. Each agency typically follows the guidelines summarized in chapters 14 and 16 of the Interagency Standards for Fire and Fire Aviation Operations [87], which acts as an excellent collection of resources for further standards and guidance. Chapters 30, 40, and 50 of the National Interagency mobilization guide also provides more detail [113]. Because they are often classified as machinery, each apparatus comes with an operator's manual or handbook that outlines, in detail, standard operating procedures, safety protocols, maintenance schedules and procedures, and troubleshooting. The design of the vehicles, especially the aircraft since many are re-purposed military aircraft, have an associated military specification that ensures consistency among different manufacturers. These can be found on [114]. Basic standards are also summarized in PMS 200 or the USFS website [115] [116]. Every day, each station must perform a readiness checklist signed off by the assigned unit, an example of which can be found here [117]. The purpose of a checklist, in general, is to provide a methodical, reproducible procedure that covers many different points such that human error is minimized. These can be points of failure in critical systems, or steps that can be easily forgotten. This ensures each apparatus is ready at a moment's notice to address an incident.

4.2.5.3.3 Infrastructure and Community Resiliency Measures

Another method for mitigating risk is to bolster new and existing infrastructure to either prevent their ability to start a fire, or to better withstand a fire. Note, this ConOps does not consider any internal fire safety measures or building codes, as it is considered a separate scope and insignificant to the spread of external fire. Additionally, utility fault monitors are covered in *Section 4.2.6.1 Timely Ignition Detection*. Because forest ground cover does not often reach all the way to structural foundations, the main way for buildings to catch fire is through falling embers. That is why it is recommended that preparing a survivable zone within the property is the best protection from a wildland fire. This is an area that is not flammable, such as concrete or moist soil, and any loose fuel such as dead leaves or needles is removed. A common culprit for ignition is a wooden roof, and exposed wood or vents to the attic in the roofing eves. Additional recommendations involve repairing and closing windows and keeping trees well-spaced [118] [119]. Further retrofitting for infrastructure in high-risk areas get even more detailed, redesigning entire properties to be fire-resistant, with strategic material selection, sealing crevices, etc. [120].

From a community perspective, the best way to mitigate losses is to have a plan in place in the event of an evacuation order. This includes creating an emergency packing list, a transportation plan and route, and location of the nearest shelter. Communities can have group meetups or workshops, where community members can talk with fire experts and professionals to assist in creating these plans, as well as insurance recommendations and resources. [121] [122]. The Department of Agriculture also offers a Community Mitigation Assistance Team (CMAT), which can be deployed to affected regions to aid in these efforts [123] [124].

One of the longest running methods of community preparedness, and familiar to many US citizens, is the "Smokey the Bear" public service announcement (PSA) campaign, which began in 1944. Personifying wildland fire preparedness into a friendly forest critter provides a succinct and kind reminder to everyone that wildland fire is an ongoing risk and to stay vigilant — Smokey even has his own personal backstory to give him a life of his own. By creating a symbol of empathy and forethought, Smokey takes a complex and scary topic and turns it into a story that can be easily told and passed down through generations. Smokey the Bear also has a website, where links to much more information is available for preparing for a wildland fire [125].

PSAs in general are a means to distribute a lot of information very quickly, often utilizing clear visualizations and concise instructions to follow, and even be symbolic in nature, such as Smokey. They act as a seed to plant into the community's collective conscious and inspire further seeking out of information. The Ad Council, who helped create Smokey the Bear, tackle many tough issues, such as the Covid-19 pandemic, anti-smoking, and anti-DUI, just to name a few [126].

It should be noted that Smokey the Bear's catchy message, "Only YOU can prevent forest fires," puts the emphasis on forest fire prevention, which may make it more difficult to communicate the benefits of "good fires" like prescribed burns. Perhaps PSAs could be developed and broadcast by the Ad Council to help the public understand that contemporary wildland fire management is not limited to preventing fires.

4.2.5.3.4 What is Lacking

With the current resources available to them, the wildland firefighting community does an excellent job of preparing its staff and engaging with the community on how to be mitigate risk of a wildland fire. Additionally, new infrastructure in high-risk zones must be fire-resilient with well-defined building codes [127]. The areas of improvement identified exist in congruence to the overall increase of scope of the discipline moving into the coming years and decades. In other words, as new technology or apparatus get introduced into the methodology, so too do the preparatory actions associated need an update. For example, if a new UAV is able to conduct ignition of a prescribed burn, that pilot will need a training program and certification process for its specific standard operating procedures.

A more complicated aspect of risk mitigation lays in addressing the influence of politics, personal property, and regulations when it comes to updating outdated infrastructure and enforcing building codes. Because the scope of wildland fires is trending upwards, infrastructure that has been unchanged for decades now pose a risk. However, getting approval and widespread support for enforcement of these codes can be difficult [128]. This is most likely due to the punitive nature of enforcement, which may benefit from an alternative approach such as a PSA or even subsidizing the work. Furthermore, there has been evidence of social bias in the regions where resiliency measures are enacted, as many of these efforts require initial capital to undertake, and there is an inherent driver to protect areas of higher real estate value [129]. Many of these are merely correlated, as opposed to causal; however, it adds a dynamic worthy of consideration to increase resiliency across the spectrum: fire does not see borders. The US Department of Agriculture outlines a 10-year resiliency plan that highlights paradigm shifts that must occur for forest health, land management, community outreach, and collaboration [130] [131].

4.2.5.4 Dynamic Wildland Fire Risk Assessment

To mitigate risk as best as possible, that risk needs to be evaluated in some form. Various methods of risk assessment are available currently, such as flammability levels, weather prediction and observation, and red flag warnings. The firefighting community monitors common wildland fire ignition sources to detect fires early.

4.2.5.4.1 Fire Risk Levels and Fire Weather

FEMA has created a national risk index for a number of natural disasters, with wildland fire being one. This index is essentially a probability analysis of fire intensity and growth over tens of thousands of fire seasons, and across the entire United States; however, it provides a disclaimer that it is a very high-level approach for national situational awareness only, and local risks may require a tailored model [132] [133] [134]. Another resource is the Wildland fire Assessment System (WFAS) [135]. This is simply a repository that collects different, applicable data and puts it in one spot, such as fire weather, lightning, and ground moisture levels. Perhaps the most widely used method is the National Fire Danger Rating System (NFDRS). This is a score assigned to specific regions based on the above data, plus topography and local vegetation to provide predictions for the upcoming immediate two days [136]. This data is available to fire managers to help them make better decisions involving readiness, as well as community members and visitors for things like burn piles or campfires. Supplementary to this is a 7-day forecast extension for the local weather, via the Weather Information Management System (WIMS). The National Weather service provides bulletins for such indices, for example, here in the West Coast: [137]. Fire weather is any weather phenomena that contributes to the risk of a fire starting or spreading. Such examples of fire weather are high temperatures, low humidity and low ground moisture, high winds, and dry lightning. Across the country there are remote automated weather stations (RAWS), which collect general weather data and upload it directly to the NFDRS, or WIMS [138].

Simulation tools are often used to assist with these calculations, doing the heavy lifting converting the collected data into a map of risk factors. These tools use fuel models, ecology models, fire-behavior models, fire-danger assessment systems, weather models, and smoke models to simulate potential fire spread [139]. Analysts can adjust variables within each of these models to observe the effects of changing conditions.

Most of the fire-behavior prediction software used today is based on Rothermel's mathematical model for predicting fire spread in wildland fuels [140], such as BehavePlus [141], [142], [143]. For a comprehensive list of software and prescribed burn-planning applications, please refer to the USDA's National Prescribed Fire Program Review [139].

More:

Lake Tahoe Basin Mgt Unit - News & Events (usda.gov)

Cibola National Forest and National Grasslands - Resource Management (usda.gov)

Superior National Forest Wildland Fire Risk Assessment (usda.gov)

https://doi.org/10.2737/rmrs-gtr-315

Quantitative Wildland fire Risk Assessment (QWRA) Considerations (firenet.gov)

Understanding Wildland fire Warnings, Watches and Behavior (weather.gov)

4.2.5.4.2 Red Flag Warnings

When this data points to a high-risk day, a region may likely initiate a fire weather watch, or even a red flag warning. A red flag warning indicates that conditions within the next 24 hours will be prime for a fire to easily start, and moreover, easily spread. Named literally for the raising a red flag at high visibility points and at fire stations, a red flag warning denotes a sort of high alert PSA, such that the community is standing by in case a fire should create a situation prompting evacuations and gearing their homes for maximum fire resiliency. This is particularly useful for people with reduced mobility or livestock who may need additional time to arrange plans. Additionally, these warnings can inform utility companies to turn off power to equipment in these areas to reduce the likelihood of an equipment failure occurring during a high-risk time. Importantly, this also helps fire managers allocate staff and equipment to a region under a red flag warning [144] [145].

[A wildland fire risk assessment framework for land and resource management | US Forest Service Research and Development (usda.gov)]

4.2.5.4.3 What is Lacking

When it comes to gaps in the fire risk assessment, the challenge comes in the fact that fires are unpredictable. The factors that combine to create our current risk assessments are the main correlatives and sometimes even causes of fires, but they don't guarantee a fire will ignite. Like the challenges faced in assessing the previous year's effectiveness, the overall predictive fidelity currently available could be improved upon.

Current limits to modeling and simulation software or processing power reduces the insight gleaned and usefulness of the tools. To gain a more holistic view of the operational environment, the wildland fire community desires tools that can better predict the impacts weather has on a fire. The USDA has compiled a list of considerations for improving models, including dynamic estimates of fuel moisture, indicators of ground-fire risk, fire-behavior modeling verification and validation, sensitivity analysis, fire effects on water quality, soils, carbon-sequestration capacity, prediction of combustion in complex fuel beds and live fuel combustion, and improved emissions estimations [139].

Furthermore, real-time simulations are not achievable with current computational power. Physics-based models currently have high processing times and require large amounts of real-time data inputs. If real-time data can be collected and processing times can be reduced, near-real time predictions would enable on-ground decision-makers to make more timely and informed decisions. For example, the tabletop participants stressed that real-time fuel-moisture data fed into a model would improve fire predictions. The tabletops also revealed that current models assume single-point ignition sources, whereas real-world scenarios often have multiple and current fire models have yet to catch up with this intricacy. As more time passes between collecting data and turning it into actionable knowledge, the usefulness of the simulation output shrinks. Additionally, the quality of data fed into software has a direct impact on accuracy. Coordinators often rely on old and/or low-resolution data, which causes less accurate results.

4.2.6 Active Fire Phase

4.2.6.1 Timely Ignition Detection

Current firefighting methodology is highly skilled at containing fires in the initial attack phase before they grow to 300 acres or more and reach the extended attack phase. In 2022, CalFire responded to 7,477 wildland fire incidents, and only 36 grew to 300 acres or more — less than 0.5%. For 2020, one of the worst fire seasons for California, these numbers are 8,648 to 89, or just over 1.0% [146]. The main factor that determines whether a fire will grow to this threshold is the time from ignition to first responders on site, and by extension, how fast a fire can be detected once ignited. There are several devices and methods that exist today to assist in ignition detection, such as utility fault monitors, visual, thermal, and air quality monitors, lighting detectors, and bystander reporting. Some of these are ground-fixed localized sensors, while others are airborne or even orbital.

4.2.6.1.1 Utility Fault Monitors

A leading cause of ignition is often malfunctions in equipment associated with the electrical power grid, such as power lines, transformers, breakers, lightning arresters, buses, and condensers. A common type of sensor used to detect faults here are line sensors. These are modernized fault circuit indicators that can be placed on a power line in remote areas of the grid that monitor the current load of the line, returning a fault if nominal parameters and thresholds are exceeded. Modern line sensors can also record the waveform of the current signal to see the rate of change over time, as well as precise clocks and GPS with cellular connectivity to enable locating the fault and remote operations without a crew onsite. This assists with fault investigations for previous faults, as well as observing non-fault anomalies that may indicate a future fault [147]. Line sensor hardware used in conjunction with software forms the basis of distribution fault anticipation (DFA), which is a system that utilizes algorithms and a network of line sensors to notify personnel of these faults and their characteristics, which can expedite the repair and inspection time required [148]. Another method of detection is early fault detection (EFD) via radio frequency (RF). RF signals can be caused by abnormal electricity leakage, high levels of corona discharge into the air, or internal micro-arcing inside electrical equipment, which can be a source of ignition. Often, the power line itself acts as a waveguide and can transmit these low-level radio signals across the entire network. Sensors placed every few kilometers with GPS can detect these signals, and multiple sensors can help triangulate a fault. Upon further investigation to the local area, teams can pinpoint the fault via ultrasonic acoustic sensing and corona cameras [149]. Lastly, there are reclosers, which operate very similarly to a circuit breaker but for large-scale power transmission. When an anomaly is detected, these will prevent electrical flow to mitigate any issues resulting from the anomaly. Modern reclosers also are capable of continuously testing the line to see if the anomaly has subsided and will automatically turn electrical flow back on if the line is in good health or remain off if not. However, after multiple attempts it will consider the issue permanent and remain off. Reclosers also assist in locating faults because they are able to separate out the faulted areas from the grid [150] [151].

4.2.6.1.2 Visual and Thermal Imagery

A great way to detect a fire is to simply watch the horizon. One of the oldest methods of fire detection are manned towers called fire lookout towers, placed atop mountain peaks or otherwise good vantage points with large line of sight distances. A seasonal employee is deployed and reports to their assigned tower, and lives there for the entirety of fire season. These towers provide a shelter with basic amenities and survival kits for the worker, with windows 360-degrees for observation. Included inside is a radio for reporting fires or other emergencies and binoculars. These towers often also have a lightning rod with copper wire down to the ground to purposely attract lightning, to minimize strikes in the surrounding forest. If the observer spots smoke, they must determine its location using an Osborne Fire Finder, which allows them to precisely measure azimuth at two locations just feet apart to enable triangulation [152]. While this approach is dated, some are still actively used. Likewise, the existing infrastructure can easily be repurposed for modern methods in a quick and cost-efficient way.

One such method are camera-based wildland fire detection systems, which are gaining popularity due to advances in machine learning and image processing techniques as well as GPS. These systems place electro-optical (EO) and infrared (IR) cameras atop similar peaks and vantage points or on UAS in high-risk areas to provide camera feeds for fire detection analyses. During the day, this is typically done with image post-processing algorithms and machine learning to detect smoke trails from EO cameras and fire luminance and temperature from IR cameras at night or otherwise low-visibility times [153]. In California, the ALERTCalifornia system, created by UC San Diego, has proven effective in all the above. They have EO cameras performing 360-degree sweeps in 30-degree increments every two minutes all throughout the state, which can see 60-miles on a clear day and 120-miles on a clear night [154]. On their active cameras page, the yellow, orange, red, and purple target lines show which cameras have recently moved, which may indicate a possible fire. When two cameras' lines of sight intersect, the location of the fire can be isolated with high accuracy. Additionally, there are satellite-based cameras, such as NASA and USFS joint effort, the Fire Information for Resource Management System (FIRMS) [155] [156]. This system utilizes MODIS (an instrument on board NASA's Terra satellite) and VIIRS (an instrument on board a joint NASA/NOAA satellite) to image temperature and air quality globally from their polar orbits, which can spot irregular spikes that indicate a possible fire with sub-1km resolution within an hour of the satellite passing over.

[The FireWatch System - FireWatch Australia]

4.2.6.1.3 Air and Smoke Monitors

A cheap and minimally intrusive method of detection is to place air sensors in a nodal network configuration. These sensors can collect localized air composition information, such as humidity, carbon monoxide, carbon dioxide, nitrogen oxides, or other chemicals typically associated with combustion and smoke [157]. These are often low power, operate on solar, and can connect wirelessly to each other for remote data transmission. When in a nodal network configuration, they can also assist in homing in on a fire's location by creating a low resolution "heat map" of the area when comparing their levels to wind direction [158]. Sensors like these have already proven effective, and commercial products are starting to gain funding for large scale deployment [159] [160]. The EPA also offers standalone kits to detect particulate matter ($PM_{2.5}$), volatile organic compounds (tVOCs) and black carbon, and even a mobile unit called the Vehicle Add-on Mobile Monitoring System (VAMMS), which can assist workers on-site monitor an area without needing to constantly watch the horizon [157].

4.2.6.1.4 Lightning Detection

Lightning is a powerful ignition source that is easily spotted, so it's unsurprising that it gets attention as a low-cost method for effective detection. In addition to general observation, there are a few sophisticated methods to refine an area of search after a storm. When lightning occurs, whether cloud-to-ground or intra-cloud, it emits radio waves from the high currents formed in the bolt. Much like other sensors, there are both ground-based and satellite-based systems that can detect these radio signals. The ground-based system is simply a network called a Lightning Mapping Array (LMA), which is an array of up to 20 very high frequency (VHF) antennas spaced several kilometers apart in an area approximately 80-km in diameter and collect radio noise at high fidelity time intervals of 20-100 nanoseconds. To distinguish the radio signal from background noise, the signal needs to be corroborated by a minimum of three different antennas and triangulated by time of arrival [161] [162]. There are many different LMAs around the world and United States, to have the wide coverage needed. The main satellite-based system, called the Geostationary Lightning Mapper (GLM), utilizes the GOES-16 and GOES-17 satellites launched in 2016–2018. These satellites capture light from the flashes as seen from space, by isolating the frequency band specific to lightning in the electro-magnetic spectrum [163].

4.2.6.1.5 Bystander Reporting

No matter where, when, or how someone suspects a fire has broken out, they should always call their country's emergency response phone number to report it (911 in the United States and Canada, and 000 in Australia). There are also several smartphone apps, such as the FEMA app or the American Red Cross app which can centralize preparedness and alerts, including evacuation notices, and often have a direct link to call 911 to report an emergency. For anyone out of range of cellular coverage or who don't possess a satellite phone, utilizing and monitoring amateur "HAM" radio frequencies can be a life-saving way to send an emergency message remotely. The main frequency for this purpose is 146.52 MHz [164]. Additional methods for reporting are valid, although less direct such as social media reporting. Many local fire agencies support X (formerly Twitter), Meta (Facebook, Instagram, Snapchat), and other social media messaging on these platforms, and host non-emergency phone lines for reporting concerns or tips, such as suspicious activity that could indicate arson, or equipment in disrepair that poses a future risk.

4.2.6.1.6 What is Lacking

Supposing a potential ignition has been detected, imperfections arise when determining the next steps. Currently, there is no standard method for prioritizing resources to some ignitions over others. For example, depending on forest health, some ignitions may need immediate response, while others should be left as a natural part of the ecosystem [165]. Additionally, while technology can have statistically high confidence in theory, it can be difficult to translate that into real-world use. Because wildland fires have large consequences if we miss a detection, we still require confirmation by human observation to make the final say. That is, we still deploy workers on-site despite sophisticated methods of detection, especially in remote regions. Much of this comes from the various forms of latency and false negatives or positives in the detection methods, which can always be further refined. For example, cameras can often confuse clouds and smoke, where a false positive is just a cloud, or a false negative is indeed smoke that looks like a cloud. Likewise, the plume may be too distant or not behave as expected based on weather conditions — all of which require human intervention to make the final determination. Another issue is the ability to pin-point a fire location, due to the limited scope of sensor ranges. With satellites, a huge issue is latency because they only pass a particular region every few hours or days, which makes constant surveillance of high-risk areas difficult. In addition, once a satellite is deployed, the technology cannot be adapted until a new satellite replaces it, which can take years to justify the cost. Lastly, there is the common issue of connectivity, data transmission, and power use in remote areas. Some of these sensors must limit how much data and processing capabilities they incorporate since they must be off the grid and low maintenance. Solar power can be spotty or simply not enough for some of the available sensor options. Ultimately, sophistication is proportional to detection confidence, and there exists a large trade-off between sophistication and feasibility when it comes to remote sensors.

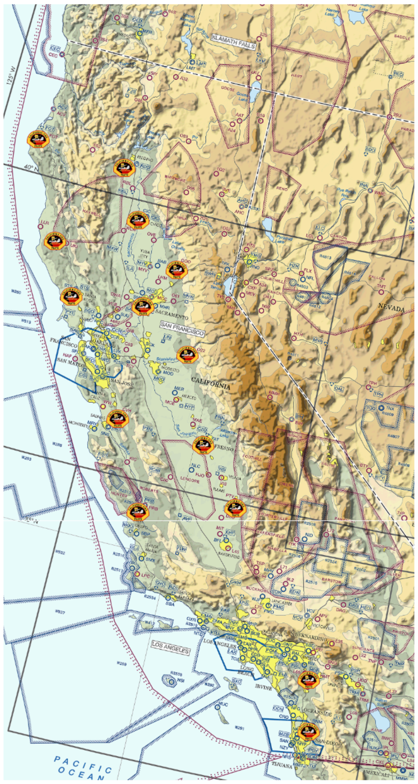
4.2.6.2 Rapid Initial Attack

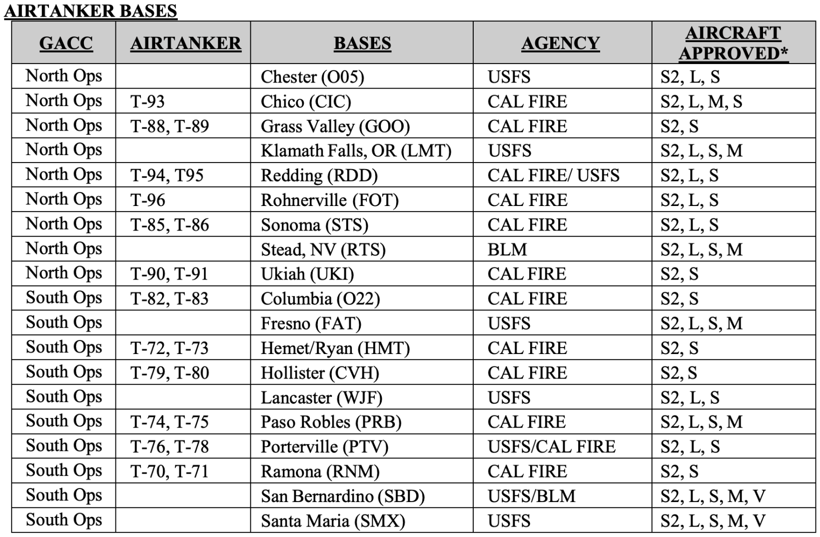
Rapid initial attack, which often is associated with the first 24 hours after ignition, is one of the most well-defined and practiced parts of current wildland firefighting capabilities. Once a fire has been detected, operations happen fast. For example, CalFire's goal is to have personnel on site anywhere in California within 20 minutes of an incident being reported [166]. To do this, agencies across the US must have their assets positioned strategically to make ingress possible in this short time and always be ready to go at a moment's notice. Likewise, operations and methodologies must be well-practiced but flexible to unique environments, with routines in place for a variety of situations. California alone has over 60 aerial assets, consisting of both fixed wing and rotary assets, while Australia has over 150, and Canada has about 40 [167] [168] [169].

4.2.6.2.1 Strategic Placement of Assets

As mentioned, there is no overarching common operating picture for all the US wildland firefighting agencies. To understand how they operate, an agency must be observed individually. Because of its large land area and impacted fire seasons, California serves as a good example of how these agencies place their assets. In California, there are a total of 25 aerial bases (14 air tanker, 11 helipad), and more than 11,000 full-time and seasonal employees. CalFire operates on the hub and spoke methodology, with the Aviation Management Unit centrally located at Sacramento McClellan Airport [170]. The state is split up into two Geographic Area Coordination Centers (GACC), northern and southern, with bases in Redding and Riverside, respectively. Then, assets are further divided by base. The way assets are allocated depends on these sub-region preparedness levels, which are associated with the local fire risk level. When one region enters a higher preparedness level, assets from the other regions mobilize to that region to bolster its readiness [171].

For airtankers, the NWCG's PMS 508 outlines this process fully [172]. There are two kinds of bases, permanent and temporary, denoted by the permanence of wildland firefighting infrastructure such as retardant loading and storage equipment, and the stationing of personnel. However, the USFS must pre-approve any temporary base prior to operations. Pages 93–96 in chapter 50 of the mobilization guide lists every asset and base in detail, and chapter 60 lists what sort of information is available to allocate resources effectively [171].





AIRTANKER BASES

GACC	AIRTANKER	BASES	AGENCY	AIRCRAFT APPROVED*
North Ops		Chester (O05)	USFS	S2, L, S
North Ops	T-93	Chico (CIC)	CAL FIRE	S2, L, M, S
North Ops	T-88, T-89	Grass Valley (GOO)	CAL FIRE	S2, S
North Ops		Klamath Falls, OR (LMT)	USFS	S2, L, S, M
North Ops	T-94, T95	Redding (RDD)	CAL FIRE/ USFS	S2, L, S
North Ops	T-96	Rohnerville (FOT)	CAL FIRE	S2, L, S
North Ops	T-85, T-86	Sonoma (STS)	CAL FIRE	S2, L, S
North Ops		Stead, NV (RTS)	BLM	S2, L, S, M
North Ops	T-90, T-91	Ukiah (UKI)	CAL FIRE	S2, S
South Ops	T-82, T-83	Columbia (O22)	CAL FIRE	S2, S
South Ops		Fresno (FAT)	USFS	S2, L, S, M
South Ops	T-72, T-73	Hemet/Ryan (HMT)	CAL FIRE	S2, S
South Ops	T-79, T-80	Hollister (CVH)	CAL FIRE	S2, S
South Ops		Lancaster (WJF)	USFS	S2, L, S
South Ops	T-74, T-75	Paso Robles (PRB)	CAL FIRE	S2, L, S, M
South Ops	T-76, T-78	Porterville (PTV)	USFS/CAL FIRE	S2, L, S
South Ops	T-70, T-71	Ramona (RNM)	CAL FIRE	S2, S
South Ops		San Bernardino (SBD)	USFS/BLM	S2, L, S, M, V
South Ops		Santa Maria (SMX)	USFS	S2, L, S, M, V

Figure 8. CalFire's 14 Air Attack Bases [171] [172].

Agencies in the US have several types of aircraft, as outlined in the federal mobilization guide and redbook [113] [87]. Below is a non-exhaustive list of common aerial assets used in the US [173].

TABLE IV
COMMON AERIAL ASSETS USED IN THE US [173]

Aircraft	Wing Type	Engine	Max Speed (KTS)	Mission Description
Grumman S-2T	Fixed	2x1650hp Turbo Prop	235	Light Airtanker
North American Rockwell OV-10A	Fixed	2x715hp Turbo Prop	250	Air Tactical Aircraft
North American Rockwell OV-10D	Fixed	2x1040hp Turbo Prop	250	Aerial Supervision Lead Plane
Beechcraft King Air 200	Fixed	2x850hp Turbo Prop	260	Trainer
Bombardier CL-415	Fixed	2x2380hp Turbo Prop	180	Water "Super Scooper"
Lockheed Martin HC-130H	Fixed	4x4300hp Turbo Prop	350	Large Airtanker
British Aerospace 146	Fixed	4x Turbo Fan	425	Large Airtanker
McDonnell Douglas MD-87	Fixed	2x Low-Bypass Turbo Fan	460	Large Airtanker
McDonnell Douglas DC-10	Fixed	3x Turbo Fan	475	Very Large Airtanker
Boeing 747-400	Fixed	4x High-Bypass Turbo Fan	520	Very Large Airtanker
UH-1H Super Huey	Rotary	1x1800hp Turbine	110	Water drop and SAR
Sikorsky S70i	Rotary	Twin Turbo, 1994hp	140	Water drop and SAR

In addition to its 60-plus fixed wing and rotary aircraft, CalFire also owns over 3,000 ground support vehicles. Not only are these classic fire engines — of which there are six different models — but there are also mobile kitchens, mobile communication centers, bulldozers, crew transports, ATVs, snowmobiles, and even insect control vehicles [174] [175].

Every day, the Federal 1000 Report is generated and published at 10:00 AM, listing the status of every asset nationally, and accessable by each agency's intelligence personnel. Locally, every agency posts a daily situation report, or "sit report," which compiles the relevent information from the 1000 Report as well as local incident status for the fire managers. The regional GACC is in charge of fullfilling asset requests from local fire managers, and therefore must be notified if any aircraft has a status change due to changinging conditions of staffing, maintenance, or flight environment such as weather. This way, the fullfilment can be as efficient as possible, utilizing the closest assets to an incident. This is refered to as the "closest resource concept." As defined on page 71 of the California mobilization guide, this means any agency resource that has the shortest distance to reach a predetermined incident location first will be dispatched, and the GACC fills orders from the most appropriate source available on the basis of urgency, resource availability, delivery time, reasonable cost effectiveness, impact on other units, and consideration of the overall fire program. To ensure even wear and tear across the fleet, all tankers follow a rotation schedule, such that each aircraft of a similar mission are dispatched regularly [176]. Additionally, reserve aircraft are available such as the National Ready Reserve (NRR) or Call When Needed (CWN) aircraft for times of scarcity.

4.2.6.2.2 Initial Response

When a wildland fire is called in to 911, the report first goes to the Emergency Command Center (ECC) for the local fire department, which then alerts all local units over a state-wide intercom to alert first responders to gear up and assigns an Incident Commander (IC). This not only includes standard fire engines, but also bulldozers, crew bus, and air crew spooling up the aircraft in the appropriate GACC. The aircraft in an initial attack are often the OV-10 for aerial supervision, the S-2 for retardant drops from a light air tanker, and a helicopter for water drops. Often, aircrew begin the process of starting, or "spinning up," the aircraft before they even know where the fire is or its scope, which saves several minutes; they can be airborne within five minutes of the initial 911 call. Once on site, the Air Tactical Group Supervisor (ATGS), who sits in the back seat of the OV-10, assesses the fire from the air and begins establishing communications with the various aircraft to start strategizing the attack. They also talk to firefighters on the ground regarding priorities and basic surveillance. This can occur on several different radio frequencies, with many different people attempting to talk.

The goal of fighting wildland fires is not to extinguish the fire, but rather to contain it. This means the flames are surrounded by measures that prevent or significantly impede the progress of the fire such that it naturally burns all the fuel within the area and extinguishes itself. This also allows water resources to be used most effectively in extinguishing spot fires or other hot spots outside of the containment zone, as opposed to trying to extinguish the internal flames which often can easily overpower the first responders. This process is outlined further in *Section 4.2.6.3 Extended Attack Phase*; however, part of initial attack is to strategize this plan when the fire is at its smallest. Utilizing existing boundaries, both man-made and natural, such as roads, streams, or cliffs, can help first responders decide where to best allocate personnel to make a fire line or plan aerial retardant drops.

When a particular line is identified for a retardant drop, all ground personnel must be clear of the area for safety. Once the ATGS gives approval, the tanker pilot is responsible for making safe ingress and egress maneuvers and dropping the allotted retardant on target. The FAA's Visual Flight Rules (VFR) minimum must be followed, as defined by their Pilot's Handbook of Aeronautical Knowledge [177]. However, it should be acknowledged that not all daylight conditions that qualify as Visual Meteorological Conditions (VMC) are used to fight fires. Flight crews may arrive in the morning and not be in the air for hours because fire conditions are at a lower intensity earlier in the day [178] [179].

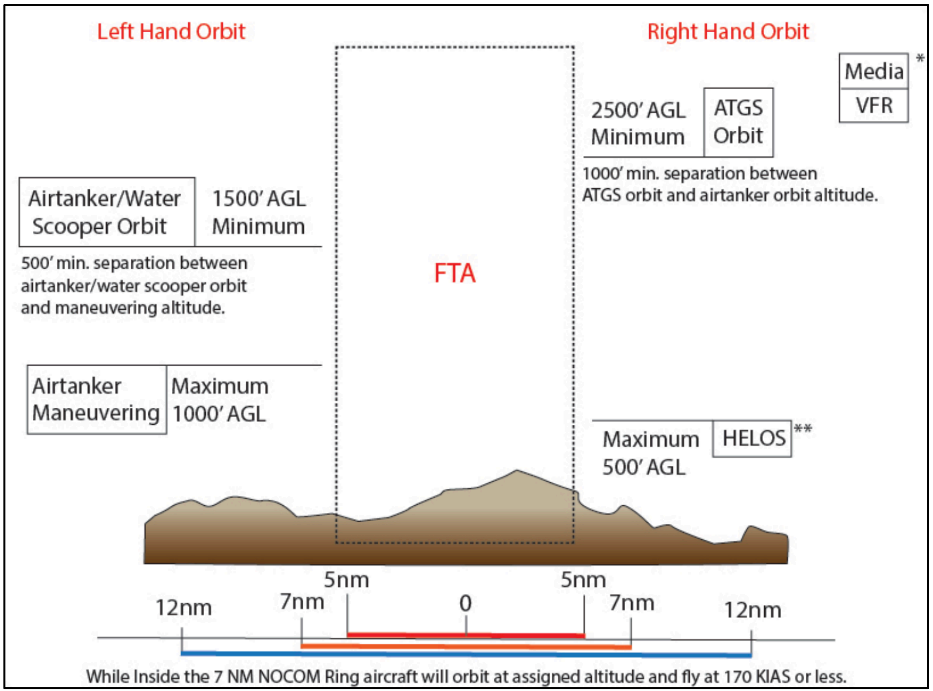
4.2.6.2.3 Establishment of an Area of Operation

When a fire is identified or detected, most NAS (National Airspace System) users are not affected. Even the largest of fires do not affect commercial airliners at cruising altitude in Class A airspace. Ideally, regulatory actions are taken only when necessary to put as few constraints on the NAS as possible. Regulating airspace is a tool for circumstances requiring a large number of aircraft or when non-participating aircraft pose a risk to firefighting operations. A fire traffic area (FTA) is set up to establish a stack of aerial assets 5 nautical miles (nm) around a central coordinate [180]. When a TFR is set up, the FTA is technically dissolved, but the stack follows a similar protocol and becomes an Area of Operation (AO). There may be multiple AOs within a TFR depending on size and complexity. When fires become larger and multiple ATGS are assigned, the area is divided with each section managed like an individual fire.

There are multiple actors able to request a TFR, but the first informal request is often made by the ATGS to the dispatch center. The default TFR is a seven nautical mile (nm) circle up to 5,000 feet above the highest terrain point. The dispatch center fills out a request form identifying the need for a TFR. The form is pushed to the GACC and the Air Route Traffic Control Center (ARTCC) with jurisdiction over the requested airspace and then sent to the Notice to Air Missions (NOTAM) office. Once the TFR is approved, the NOTAM is sent out, but there is about a 30-minute delay for visual depictions to catch up (e.g., skyvector.com, faa.gov, ForeFlight). When an adjustment needs to be made, or if a TFR needs to be reshaped, the original TFR is cancelled, and a new request must be submitted.

"The stack" is a colloquial term referring to a NWCG standard for altitude separation. Different aircraft types are assigned an altitude and stacked in a radius around a central geographic point. Examples of how to maintain vertical separation include [181]:

1. All aircraft must maintain a minimum 500 feet of vertical separation in the airspace; 1000 feet is preferred and should be used whenever possible.
2. Helicopters should be assigned between a hard ceiling (i.e., at or below 500 feet).
3. Vertical stacking of airtankers is discouraged; better to utilize an orbit altitude racetrack pattern.
4. It is common practice to put media helicopters above the ATGS to keep them away from firefighting aircraft.



* Media and IAA Aircraft: Maintain VFR separation above highest incident aircraft or at the altitude assigned by the controlling aircraft.

** Helicopters: Fly assigned altitudes, orbits, and routes.

Figure 9. Fire Traffic Area Diagram [180].

4.2.6.2.4 What is Lacking

Initial attack in and of itself serves as an excellent cross-section of the entire wildland firefighting chain, as it reflects all the efforts leading up to it, and significantly influences the efforts that follow. In that respect, improvements needed in any active fire phase are both the most obvious and the hardest to implement due to the inherent risk posed by any methodology that is different from what has been established. For initial attack, a huge issue is in the logistics of getting personnel and equipment from the road to the actual flames. Challenging topography, dense foliage, rivers, etc., can make this "last-leg" of ingress very difficult for firefighters on the ground. Another area that is lacking is communications. Firefighters need to disseminate information both en masse or to individual groups for strategic direction. Not only is communication about having connectivity for data transmission, but it is also about parsing out who needs what and when. Especially in a mentally and physically challenging environment, communication during an active fire should be easier for everyone involved, using digital apps, graphical user interfaces, standardized messages, etc. Lastly, methods of suppression are imprecise. Aerial drops of retardant and water is almost entirely done visually, with wide margins and approximate directions, as opposed to quantitative targeting. If these drops were able to hit a mark with a defined measure of precision, effectiveness could also be quantified, and in turn be more efficient and safer.

4.2.6.3 Extended Attack Phase

Although most wildland fires are contained or extinguished in the initial attack phase, fires that this ConOps aims to address and are most likely to garner worldwide attention and support, reach the extended attack phase. The transition from initial attack to extended attack can vary from fire to fire; however, several key attributes are typically associated with extended attack. Such attributes are fire size greater than 100 acres, operations exceeding 24 hours, multiple agencies involved and increased staffing, and establishing a local base camp [182]. This most often is associated to an upgraded fire incident level, where levels 5 and 4 are initial attack, and levels 3, 2, and 1 are extended attack (lower number means an increase in severity), as defined by NIFC [183]. Importantly, it is up to the initial attack Incident Commander to recognize early when a fire has expanded beyond their ability to contain, and upgrades are largely subjective.

Once initiated, the key focus of extended attack is firefighter and public safety, paramount to fire extinguishment. In that sense, initial attack methodologies are scaled up, while also re-allocated for defensive tactics, as opposed to offensive tactics: aerial suppression efforts move to protect infrastructure (as opposed to preventing fire progress), the fire behavior is monitored at a higher level, evacuation orders are given, and rescue operations stand by for firefighter and civilian extraction. In general, the complexity greatly increases during extended attack, and can often mean dealing with several different spot fires within a dynamically changing perimeter.

4.2.6.3.1 Increased Complexity and Logistics

When a fire incident is upgraded from initial attack to extended attack, the Incident Commander is responsible for collecting the information necessary for new assets arriving. The number of personnel can increase from under a hundred to up to a thousand, so everyone needs to have the same starting information. This includes an incident briefing form (ICS 201) [184] that has a map of the current fire boundaries, current resources called upon, and current strategies. Often, an incident command post and check-in locations are established. As new assets arrive, management duties divide up respective to localized areas of concern, with processes for proper transfer of authority. Whereas an initial attack may only have a few coordination roles working with a local fire crew, extended attack leadership organization grows to a large organizational structure of 19 roles for operations, 16 roles for planning, 16 for logistics, and 12 for finance. Each of these positions have their own set of responsibilities and positioning assignments, to best aid in the larger effort and act as unified command.

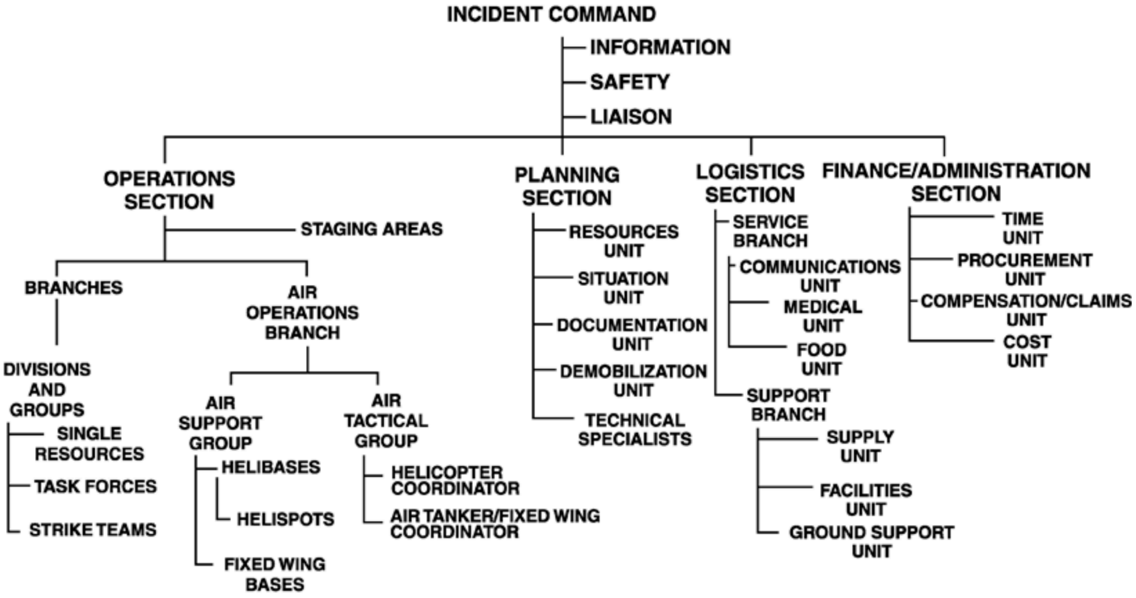


Figure 10. Type 1 and 2 incident command structure [182]

As assets are added, missions are assigned based on a priority of need. For infrastructure protection, every structure is categorized as defensible, or non-defensible. If a structure is defensible, it is well equipped to resist fire damage on its own. Some may need constant observation ("prep and hold"), while others only need to be checked after the fire passes through ("standalone"). If a structure is non-defensible, it is likely to be damaged from the fire. Some of these may be mitigated with some initial countermeasures ("prep and leave"), while others may be certainly lost requiring evacuation or rescue ("rescue drive by"). These classifications are determined by their inherent tactical challenges, such as location, size, or hazardous material, not just flammability, and ultimately comes down to a cost-benefit trade-off if resources are devoted to protecting the structure. Additionally, as the size of the fire grows, extended attack implies that groups around the edge of the fire may be relatively isolated from other resources as they become more spread out. Hence, a critical component of extended attack is to provide safety best practices, watch-out scenarios, standard protocols for equipment use, and refuge building.

4.2.6.3.2 High Level Fire Monitoring

As a fire grows into extended attack, tracking its path and size helps inform response priorities. Many of the same tools used for risk assessments and ignition detection, such as satellites and cameras, as well as weather predictions, can also be used to monitor the fire. Satellites provide the best data for determining total fire size, active fire perimeter, and spread rate on a day-to-day basis, whereas ground and aerial assets provide the best data for localized and minute-by-minute status of the active perimeter, augmented by weather forecasts. While this effort is routine for extended attack and data collection, it is rather high-level and improvements to its fidelity could assist in future assessments of effectiveness metrics as mentioned earlier.

4.2.6.3.3 Sustained Aerial Operations and Degraded Visual Environments (DVE)

Although aircraft have been actively fighting wildland fires for over 90 years, today aircraft remain largely constrained to the same narrow window of six to eight operating hours as when they first began supporting this mission. Aerial firefighting remains a largely VFR mission. As a result, this has largely prevented aerial firefighting operations during smoky daytime periods and at night. Together, this can result in 16 to 18 hours (60% to 75%) of each 24-hour operational period being unavailable to supporting aerial firefighting aircraft. Smoky daytime periods not only limit the available daytime flight support periods but have been known to continue for multiple consecutive days, depriving ground firefighters of the important logistical, suppression, retardant, surveillance, and emergency extraction support that aircraft can otherwise provide [185] [186] [187].

While there has been limited use of specially configured helicopters in night vision devices (NVD) operations, the cost, extensive training requirements, and their limited utility, make NVD a suboptimal solution. NVDs are useless during daytime smoky periods that comprise half the current nonavailability period of traditional firefighting aircraft, so this has precluded their widespread adoption across wildland firefighting agencies [188].

What is the potential impact of these limitations and the estimated return on investments that enable aerial firefighting aircraft to support the fire 24/7 and under all visibility environments? In 2018, following an in-depth study of these challenges and the successful demonstration of technology that offered to greatly expand aerial firefighting support coverage, the U.S. DOI estimated that even if a tripling of the available aerial support window from 8 to 24 hours only produced a 10% improvement in the time and area to contain wildland fires, that would still result in $300 million and 980,000 acres being saved [189]. In addition to the improvements expanded aerial firefighting coverage could have on sustained attack on established wildland fires, it also offers significant opportunities in the initial attack on emergent ignitions. In 2017, DOI conducted a study of wildland fire ignition times from 2015 to July 2017 [190]. The study found that nearly 20% of all wildland fire ignitions during that two-year period occurred outside the traditional aerial firefighting operating hours. This allowed those ignitions to grow uncontested by initial attack suppression aircraft for as many as 16 hours, likely contributing to the growth and ferocity of these fires and impacting the time, area, and resources required to contain them.

Another aspect of aerial firefighting that is often overshadowed by suppression operations is logistics flights in support of ground firefighters. It is ground firefighters who ultimately contain and extinguish wildland fires. To do that, they require steady logistical support for their water, food, fuel, and other supply requirements. This logistical support is also important when they must move en masse to pursue the fire. Due to the commonly remote nature of wildland firefighting, this logistical support is often provided by helicopters. The same extended daytime smoky periods that impact initial and extended attack operations also prevent the critical resupply of ground firefighters in the field. This exacerbates the limited hours traditional aerial firefighting assets are available to support operations.

4.2.6.3.4 Emergency Extraction and Rescue

Ensuring firefighter and public safety sometimes means rescuing personnel in distress or at high risk of injury. This is called "rapid extraction," which can occur in both ground-based and aerial forms.

Aerial rescue follows the standards for general helicopter operations in NWCG's PMS 510 [191]. Often, these rescue missions are performed by the same helitack crews used for general firefighter and equipment transportation, due to the similar mission profiles. When staging a rescue or other transportation mission, they must designate a safe landing or hovering zone free from obstacles over 18-inches tall, free of any debris, and dusty ground has been wetted. The site must also be able to withstand the rotor downwash as to not harm ground personnel or impede the overall suppression efforts. These landing zones vary in size depending on the class of helicopter, ranging from 75–110 feet in diameter [192]. A helicopter rescue can be classified as either medical short haul, where the injured party is carried via a tow line below the helicopter in flight, or hoist, where the injured party is raised and brought into the helicopter fuselage for transport. Most helicopters on scene of a fire do not have hoisting capabilities, as it requires special equipment, although it is safer for the injured party. However, both methods allow the helicopter to hover during rescue if a landing site cannot be established [193].

On the ground, designated crews also standby for extractions in arduous terrain where access from a helicopter puts others at risk or is otherwise unavailable based on the priorities of the fire. California has the Rapid Extraction Module Support (REMS), which is a pre-staged, ground-based, rescue team of 2–4 personnel assigned to large wildland fires. Its roles and responsibilities are outlined in the Incident Command System (ICS) document 223, including checklists, organization and staffing, equipment, standard procedures, and training requirements needed for extraction [194]. The REMS team gets its orders from the local group supervisor, as well as the medical, logistics, and branch directors, and team members can grow or contract depending on the scope of the extraction incident. Extractions using the REMS typically involves a 4x4 vehicle, with climbing rope, carabiners, lift devices, and harness for both the REMS team and victim.

4.2.6.3.5 What is Lacking

This investigation has identified through interviews that many coordinators want to know what assets are available to them, supported by anecdotes of their use fighting fires; finding out that the tool they want exists just across a jurisdictional border is not helpful after an incident is useless. Especially in the urgent and dynamic environment of wildland firefighting, incident managers need to put their time into the resources they have on the scene, not negotiating additional resource acquisition. Currently there is considerable competition among contracted assets. It has been left to the states to take an entrepreneurial approach in to acquiring what they need, and this causes inadequate distribution of resources, especially in preparedness level 5. This creates incentives for contracted assets to violate safety recommendations to remain competitive.

Additionally, it is difficult to share assets across agencies when those agencies hold their assets to different safety, equipment, and maintenance requirements. These standards have been outlined by the NWCG, but agencies must voluntarily agree to uphold these ordinances [195]. For example, there was a case in Montana where some of the state's assets did not meet standards for federal land and therefore could not be used [196]. Wildland fires do not know jurisdiction boundaries and it is in everyone's interest to have transparent access to regulation resources when needed. It is also best that those resources are delegated and prioritized with a large-scale, state, or national perspective of resource needs. Resource acquisition is further complicated in active emergency situations, such as preparedness level 5, where urgency is critical. Ultimately, asset sharing can be better supported with improved predictions of fire behavior. When multiple fires are being fought by different organizations, each organization wants to save their own resources in case they are needed in the future.

Another barrier to resource acquisition is the lack of readily accessible information about what resources different organizations already have. If this information were more widely available, it would be easier to share resources as situations develop. Knowing more about what data and tools other organizations have acquired, how they were acquired, and how they use them would be useful to an organization facing decisions about their own resource acquisitions.

4.2.7 Post-Fire Phase

After all flames have been extinguished and the attack teams return to their respective bases, there is still plenty of work to be done. This begins the recovery phase, which aims to stabilize the region from an environmental standpoint. This includes erosion control and flood mitigation, clearing hazardous debris, and performing forest restoration to aid the ecosystem and incorporate future fuels mitigation measures. Additionally, many of these efforts segue into the next fire cycle nicely, beginning again at the Pre-Fire phase.

4.2.7.1 Emergency Stabilization and Debris Removal

While many fire-affected regions are allowed to recover naturally, large fires and fires near critical infrastructure require additional attention. For these, the Burned Area Emergency Response (BAER) is a team of specialists in soils, hydrology, geology, engineering, wildlife, botany, and archeology who first assess a landscape after an impactful fire. Together with their expertise, they formulate a response plan and priority list to address any threat to human life, safety, property, or critical natural and cultural resources [197]. However, BAER only operates on federal lands, and does not work to correct historical degradation or determine long-term restoration plans. One of the first priorities is typically hazardous material removal. California and Oregon implement multi-phase approaches to remove material in a logical progression. These items include, but are not limited to, toxic metals and chemicals, asbestos, unstable structures such as chimneys, metal and vehicles, downed trees, and topsoil. Additionally, salvaging dead, but not fully-burned, wood for future use in timber infrastructure can be sold to lessen the recovery costs and provide an eco-friendly source of lumber [198] [199] [200].

4.2.7.2 Flood Prediction and Erosion Control

Healthy trees and ground brush aid in erosion control in several ways. The most obvious is providing a physical barrier to wind and flowing water, as well as reinforcing the soil below with their roots acting as anchors. However, another major benefit of healthy trees and ground brush is that they help retain moisture in the soil, which keeps the soil both heavy and porous. Because of this, a well-known outcome from a sudden loss of trees and brush across a burned landscape is the possibility of a sudden large amount water and loose dirt on top of solidified, non-porous rock. Combined with often mountainous terrain, this poses a major risk of mudslides and flooding due to the increased exposure and lack of water absorption in the ground. To predict which areas are most at risk, the US Geological Survey published a scientific approach to assess a region's flood risk level, very similar to the prediction of fire risk mentioned in *Section 4.2.5.4.1 Fire Risk Levels and Fire Weather* [201], as well as NOAA's severe weather tracker. High risk zones can become areas of focus for debris removal, erosion control, PSAs, and temporary flood blockades. However, another, long-term consequence of a loss of trees and brush is the impact on the natural watershed. Rivers and streams can be blocked or diverted, snowpacks melt earlier in the year and don't absorb into the ground as deeply, and toxic materials and debris can more easily flow into it. All of which impact the ecosystem and local economy. There are programs provided by the US Department of Agriculture in place to assist in watershed resiliency, such as the Emergency Watershed Protection Program (EWPP) and the Watershed and Flood Prevention Operations (WFPO), although they require certain sponsorships and requirements to be eligible

[202]. Most watershed protection resides in erosion control in the regions most at risk. The Tahoe Conservancy, perhaps most well-known for its “Keep Tahoe Blue” campaign aimed specifically at this topic, has a strategic plan in place for continued ecological restoration projects and landscape architecture [203]. Specific erosion control techniques are a discipline in and of itself, with many private contractors supporting them on this effort. CalTrans even provides a thorough list, ranging from soil health, short term prevention, long term prevention, slopes, and storm water treatment [204]. Most methods ultimately require some aspect of revegetation, to reintroduce this long term, passive, and natural resiliency.

4.2.7.3 Forest Restoration and Fuels Planning

In a severe burn area, it can be difficult for a forest to recover naturally, as seed banks underground have been damaged, and the seeding trees have been destroyed. Likewise, any new tree growth struggles to compete with other bushes and grasses, which need far fewer resources and grow much faster. Manual intervention assists in fostering young forest growth through strategic use of native species and climate-resilient seeding. Additional measures ensure young trees can make it to a more mature growth state through seed extractories and nurseries, which can then be delivered and planted across the United States in different forests to encourage maturation diversity. As a forest grows, the USFS employs a systematic “silviculture,” or science of tree growth, wherein every measure taken is associated with a prescribed treatment plan [205]. This process is outlined in detail in relation to erosion prevention in Sections 2 and 4 of the *Tahoe Conservancy’s Revegetation Guidance Document for Erosion Control Projects in the Tahoe Basin* [206]. Revegetation practices are not just about dropping a bunch of seeds; it is a practice of preparation, facilitation, and continued protection to establish a healthy patch of forest. This includes soil preparation, seeding technique, removing invasive and dominate plants, providing energy sources for sub-ecosystems that aid in the plant lifecycle, such as pollinating insects and decomposers, or providing physical barriers of erosion such as logs and soil blankets. When selecting which kinds of plants, several factors are considered, such as growth profile, nitrogen sequestering, life span, invasive/native to the region, and dominance tendencies. Since 2021, these efforts have been aided by federal funding, thanks to the REPLANT ACT [207].

4.2.7.4 What is Lacking

A few challenges are present in the current state of wildland fire recovery. First is the ownership of land. Private properties are responsible for their own maintenance and restoration, which often does not occur due to a lack of enforcement and high cost. Additionally, state and federal landowners have difficulty securing funding for these efforts, as the scope has greatly increased in recent years with more severe fire seasons and harsh winters. Another challenge is that the science of revegetation involves the entire system, not just one focused component. This means it takes much more planning and coordination, as well as prediction up to decades in the future. Given the relative permanence and impact it can have, it also requires much more approval and community support in advance. Likewise, quantifying the effectiveness and success of revegetation projects requires monitoring over this long timespan. Often this means that in a bid-proposal scenario a revegetation solution will likely be bypassed by a quick fix civil construction solution. Finally, a large gap identified is the public knowledge of these measures. In general, people know wildland fires are a danger and that effort to prevent them in a smart way is a good thing; however, this is easily forgotten during times without fire, such as Winter or Spring. In essence, these “long-game” proactive methods don’t get the attention they need to be fully effective, despite potentially saving taxpayer money in the long run.

4.2.8 Priorities Among Changes

Pending input from community and reviewers.

5 Future State

5.1 Purpose

The purpose of this *Future State* section is to identify the approaches, technologies, funding, and organizational changes that, if followed, would result in substantive progress in resolving the gaps and challenges identified in *Section 4: Current State of Wildland Fire in the U.S.* of this ConOps. It provides a desired future state based on current and developing technologies that illustrates the art of the possible.

Achieving the desired future state improvements requires a thorough understanding and thoughtful consideration of the technology development and the strategic planning, program management, staffing, and budgeting and funding factors that are inherent to government operations. Accordingly, a prospective timeline of implementation was developed, outlining the detailed technology and government readiness characteristics along the future continuum from near term, mid-term, far term, and visionary states. The desired future state described in this section is set in the visionary future state (11-15 years in the future).

While many government, industry, and academic reviews and assessments have been conducted over the years, none have outlined a detailed desired future state. This *Future State* section strives to fill this gap, providing a foundation on which a future state of wildland fire technology roadmap can be collaboratively developed and executed by appropriate government, industry, academia, and philanthropic stakeholders.

5.2 Background

As has been previously described in the Current State of Wildland Fire in the U.S., the increasing intensity of wildfires and their escalating economic and human losses have reinforced the imperative of addressing this national issue. The recent wildfire tragedy in Maui serves as a stark reminder of the immediate need for deliberate, focused, and accountable action [208].

5.2.1 White Papers, Tabletops, Interagency Community, and Industry Involvement, Government, Industry, Academic Reports, and Public Reporting

The foundation of the material in this *Future State* section is the extensive work to engage a wide variety of wildland fire stakeholders. Extensive interviews with experienced wildland fire managers, frontline hand crews, smokejumpers, incident commanders, resource allocators, and aviation specialists were conducted in support of focused white papers that were used to support multiple interagency tabletop exercises, used to further the identification of current wildland fire gaps and challenges to be addressed in the desired future state. Additionally, substantial effort was made to review the dozens of government, industry, and academic reports and papers that outline and, in many cases, reinforce the current gaps and challenges in modernizing wildland fire. Among those reports was the February 2023 President’s Council of Advisors on Science and Technology Report to the President – Modernizing Wildland Firefighting to Protect Our Firefighters [209].

Realizing that wildland fire is a subject that can evoke strong views and vigorous discussion, substantial efforts were made to access and consider an inclusive and diverse array of work and views on this subject. Citations have been extensively used in this *Future State* section to provider the reader with access to many of these resources.

5.2.2 Areas of Interest/Concerns

The development and application of new technologies to wildland fire management is a high interest item in addressing this national issue. However, technology alone will not be able to resolve all the challenges that face wildland fire today. There are also issues inherent in the current wildland fire space that have stymied previous attempts to modernize wildland firefighting technology. The analysis a proposed Future State will address these issues, including, but not limited to:

- Organizational Structures
- Culture
- Strategic Policy Focus
- Political Focus
- Public Focus
- Funding
- Technology Staffing
- Firefighter Safety
- Human Factors
- Training

5.3 Stages Along the Road to Future State

5.3.1 Key Assumptions and Dependencies

The following key assumptions and dependencies apply to the following description and discussion of the desired future state.

- The “future” is not a single point in time, but rather a continuum of steps where small gains serve to both improve current operations and establish a foundation on which follow-on gains grow.

- The ConOps desired future state represents a specific point, described in the context of this continuum.
- While dependencies of desired future state advancements may be articulated, the detailed description and sequencing of technology developments along the preceding steps of the continuum are covered in the separate, Technology Roadmap publication.
- High impact (particularly life safety) wildland fire mitigation and management improvements with low tech, integration requirements, and cost barriers to adoption options will be prioritized first.
- Lower impact technologies, but with similar low tech/integration/cost barriers to adoption ("low hanging fruit") will receive second priority.
- Cultural adoption strategies are integral to the successful implementation of the desired future state. If cultural challenges are not adequately identified and addressed, they can represent far greater barriers to adoption than the technology challenges. The cultural adoption strategy for achieving the desired future state will consider the equities of interagency government stakeholders (at all levels), industry, philanthropic, and academic partners as well as those of the affected public.
- Agency funding levels (including understanding the structure and available discretionary levels of agency budgets) must be appreciated and fully considered in future state planning.
- While traditionally the focus of future improvements has centered around the Active Fire phase, enhancements across any of the three wildland fire phases (Pre-Fire, Active Fire, and Post-Fire) and their 7 sub-links (3 Pre-Fire, 3 Active Fire, and 1 Post-Fire) will result in some measure of wildland fire mitigation (see *Sections 5.4–5.5 and 5.8–5.10*). This concept is aligned with the aviation/industrial mishap chain methodology; if steps are taken to mitigate the risk of the mishap ever occurring, the overall "safety system" improves.
- Technologies that bring success in one phase (i.e., remote sensing, data analytics, etc.) may also be applicable in furthering future goals in other phases/links.
- Outcome effectiveness measures are key components of any future state discussion. "If you can't measure the outcome effectiveness, how do you know it worked?"
- Progress no matter how slight is still progress; quick wins fuel the inspiration engine of future progress on more difficult opportunities.
- All data has value, no data is perfect and absolute, and all data (and the supporting analytics) should always be the subject of continual scrutiny and improvement.
- The desired future state will comply with all applicable federal regulations and interagency wildland fire policies and standards.
- Technologies described in the desired future state are implemented in support of ground firefighters. Wildland fires are contained and extinguished by firefighters on the ground and any technologies that enhance their safety or improve their effectiveness will have a positive outcome on wildland fire mitigation and management.
- Technologies discussed in the desired future state will only be integrated wildland fire operations following rigorous collaborative build-up testing and the development, implementation, and completion of hands-on training for wildland firefighters who will directly use or benefit from these technologies.

5.3.2 Near-Term, Mid-Term, Long-Term, and Visionary Waypoints

One of the key assumptions in addressing the desired future state of wildland fire is that the future is not a single point in time, but a continuum. Progress towards the desired future state will occur across a series of waypoints that enable iterative improvements and adoption. Waypoints along this continuum are not merely defined by technology readiness levels (TRL). Government funding levels, realities of budget cycle constraints, staffing, program, organizational culture, and policy considerations also play a role in defining what can be accomplished at each waypoint and the successful implementation of any proposed technology along the continuum. ConOps that neglect to consider the full range and dependencies of these considerations often fail to reach their desired future state. For planning purposes it is useful to group the times into four periods: Near-Term, Mid-Term, Long-Term, and Visionary, as and shown in Figure 11, and defined in the following *Sections 5.3.3 – 5.3.6.* The purpose of this ConOps is to describe the desired future state. Within the context of the future continuum waypoints described below, the desired future state is envisioned to occur in the Visionary (11-15 year) milestone. The detailed outline and description of accompanying technology developments in the supporting waypoints can be found in the separate Technology Roadmap document.

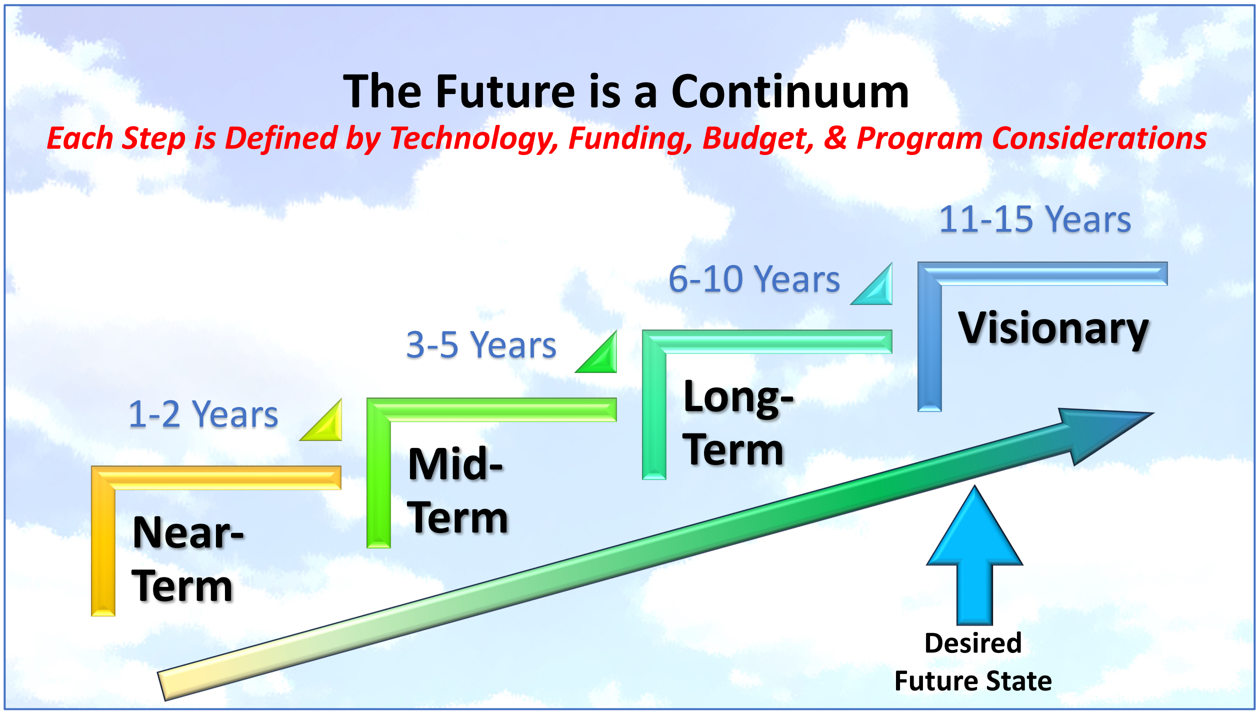


Figure 11. The Future is a Continuum. The Desired Future State is Focused on the Visionary Milestone.

5.3.3 Near-Term: 1 – 2 Years

- Technology system is mature and fielded in other industries/use cases. TRL 7 – 9.
- Technology needs little to no customization to meet wildland fire requirements for a minimally viable product (MVP).
- Meets the cost constraints of current wildland fire agency budgets.
- Requires little to no additional integration and training.
- Can be phased into the subject mission set as part of a risk-reduction strategy.
- Bottom line: technology is field ready, does not require additional agency funding, requires little to no training, and is generally accepted by the workforce as immediately necessary and ready for use in a prudent, phased approach.

5.3.4 Mid-Term: 3 – 5 Years

- Technology system has been demonstrated in a relevant mission environment (not necessarily the one for which it is ultimately intended) but has not been fielded in other industries/use cases. TRL 6.
- Requires customization to meet wildland fire requirements for MVP.
- Aligns with current agency strategic plans and could be tied to specific ongoing and/or future initiatives outlined in these documents and/or current programs. Implementation and management of this New Technologies could fit within the existing agency/interagency wildland fire organizational structure, but would likely require additional staffing resources, including some with new skill sets/background.
- Available current budget/appropriation funding is insufficient to support completing necessary development, testing, and fielding. Additional funding requires either agency budget reprogramming or Congressional appropriation action.

5.3.5 Long-Term: 6 – 10 Years

- Technology component(s) have been validated in a laboratory environment and in an industry relevant use case environment, but not specific to the intended wildland fire mission. TRL 4 – 5.
- Requires identification and integration of wildland fire requirements to influence the current and future direction of this technology development.

- Applications for this technology are largely beyond the concepts currently expressed in agency strategic plans, programs, and funding initiatives. Requires additional strategic and program planning.
- Research, development, developmental and operational testing, and field integration funding for this technology are not currently included in agency budgets/plans. Requires new/additional appropriations.

5.3.6 Visionary: 11 – 15 Years, The Desired Future State Timeframe

- Basic principles underlying this technology have been observed and reported. Initial work on the technology concept and the potential wildland fire application has been conducted and an experimental critical function and proof of concept have been identified. TRL 1 – 3.
- Potential alignment with and integration to the wildland fire mission space is unclear and thought related to this is in its infancy.
- The potential cost and time to research, develop, test, evaluate, and field this technology in the wildland fire mission is unknown.
- Current agency strategic plans and programs do not mention this technology and its potential applications. There is no current wildland fire agency funding for research, development, and testing of this technology.

5.4 The Three Phases of the Wildland Fire Lifecycle

Wildland fire is influenced by several factors that are all interconnected as a system of systems (Figure 12). Understanding this system of systems and the interdependencies of the component parts is key in developing strategies, plans, and technologies to achieve desired future state goals. At the highest level, there are three widely accepted phases of the wildland fire life cycle, Pre-Fire, Active Fire, and Post-Fire.

- The Pre-Fire phase of wildland fires includes activities carried out before an active fire for a given location occurs. These generally include preparation, assessment, and mitigation activities. For decades, key elements of the Pre-Fire phase were neglected, with most of the internal and external interest, resources, and technology focused on the subsequent Active Fire phase.
- The Active Fire phase begins when a wildfire ignition is first detected. Activities in the Active Fire phase are focused on containing and extinguishing the wildfire and take many forms (active suppression, logistics, management, communications, etc.). Historically, the Active Fire phase has and continues to receive most of the public/media interest, government focus, and funding. As the wildfire is contained and eventually extinguished, the lifecycle transitions to the Post-Fire phase.
- The Post-Fire phase commences when a burned area is safe to enter, and resources are available to begin conducting Post-Fire activities. This can occur before the entire wildfire is contained and extinguished depending on the specific conditions and factors of the individual wildfire. Post-Fire activities can continue for years depending on the landscape circumstances.

Figure 12. The Three Phases of the Wildfire Cycle and the Opportunities of Overlapping Technologies.

- While each of the wildland fire phases have unique activities and technological requirements, they also share commonalities. As an example, big data analytics, modeling, and simulation, data visualization in decision support, and ground, space-based, airborne, and social media-based remote sensing technologies have important roles across all three phases. However, decades of resource, policy, and the public's concentration on the Active Fire phase have decidedly skewed government, industry, and academia's focus toward technologies focused largely on this one component of the wildland fire system. Conversely, the Desired Future State discussion will adopt an all-inclusive approach that considers technological and organization enhancements across the 3-phases. This is consistent with previous high-level government wildland fire strategic thinking, including:
- The National Cohesive Wildland Fire Management Strategy, Addendum Update 2023 [210].
    - Page 18: "the wildland fire management system needs a systems analysis and a holistic approach to address the realities of today's rapidly evolving wildland fire environment."
- Executive Order 14072, Strengthening the Nation's Forests, Communities, and Local Economies of April 22, 2022 [211].
    - "To strengthen America's forests and advance a holistic, science-based approach to wildfire resilience and forest restoration, this Executive Order advances action on data collection and analytics, climate-smart stewardship, and enhanced coordination."
- NIST Offers First-of-a-Kind Guidance for Holistic Home and Community Wildfire Protection, March 1, 2022 [212].
- It is also notable that this approach to provide technological decision-making support across the three phases of the wildfire system has also been adopted by the European Union (EU) and their long-running SILVANUS wildfire project [213]. SILVANUS and the EU define the 3-phases as preparedness, response, and recovery.

5.5 The 7-Links of the Wildland Fire Chain

While the three wildland fire phases provide a useful strategic framework for illustrating a high-level view of the wildland fire lifecycle, they lack the granularity necessary to develop and apply specific technologies and methodologies to the defined operational use cases and subsequent sub activities present within each phase. To facilitate this, we further break down the three phases into seven component categories that like the phases are inextricably linked within the wildland fire management system of systems. We characterize these as the links in the Wildland Fire Chain (Figure 13). This terminology reinforces the fact that work (or the lack of) in one link influences the risk and performance in the adjacent link and the overall strength of the overall system is dependent on the strength of the weakest link in the chain. This impact then cascades to follow-on links, affecting the overall performance of the wildland fire system. Here is one example of how that cascading can occur across wildfire chain links:

- If a thorough, data-supported Pre-Fire risk assessment is not conducted, the resulting lack of information necessary for land managers to apply scarce resources to Pre-Fire Mitigation projects, like prescribed burns results in suboptimum decision making.
- Not only does this reduce the effective application of active Pre-Fire Mitigation measures, it complicates the challenge of maintaining a dynamic Pre-Fire risk assessment due to a lack of data.
- Resultant challenges in determining the dynamic risk of wildfire can result in less predictable ignition starts and larger, more aggressive fires that had its roots in suboptimal assessment of the Pre-Fire risk and resultant misplaced Pre-Fire Mitigation activities that could have reduced the hazardous fuels risk.

The impact of neglecting one or more links in the wildland fire chain has manifested itself time and again in some of our most costly and deadly fires [214]. Neglect of the Pre-Fire Active Mitigation link and over emphasis on the active fire links in an effort to quickly suppress every wildfire have been proven causal factors behind the steep growth in megafires [215], [216]. Most recently, the deadly Lahaina fire on the island of Maui (which as of this writing had claimed 96 lives) stands as testimony to the perils that neglecting one link of the wildland fire chain can have on adjoining links and the overall performance of the system. Local Maui government had known of Lahaina's increasing wildfire risk for years. In the county's 2020 hazard mitigation plan, they identified 132,000 acres of land requiring long-term fuels management and the need for 70 miles of fire brakes and 90 miles of fuel breaks to help reduce fire intensity [217]. However, fulfilling those requirements would require significant amounts of money and collaboration among landowners. As has been repeated across the U.S. in the face of similar reports, key activities in the active Pre-Fire mitigation link were put off. As a direct result of not adequately attending to this link in the wildland fire chain, when the wildfire at Lahaina ignited, it was fueled by years of built-up fuel, including highly flammable non-native grasses that further intensified the heat and spread rate of the fire [218].

While disregarding or failing to pay the requisite attention to any one of the wildland fire chain links can have adverse impacts on one or more other links in the chain, it has also been shown that positive results in one link can mitigate the risk in other links and improve overall system performance. A recent example of this was in the Lick Creek Fire of 2021. A post-fire review revealed that proactive hazardous fuel treatments conducted in the area resulted in less aggressive fire behavior, which provided fire managers with greater options in combatting the fire [219]. In the end, the Lick Creek Fire was shorter in duration, less costly, and resulted in less severe landscape damage because of the previous hazardous fuel treatments.

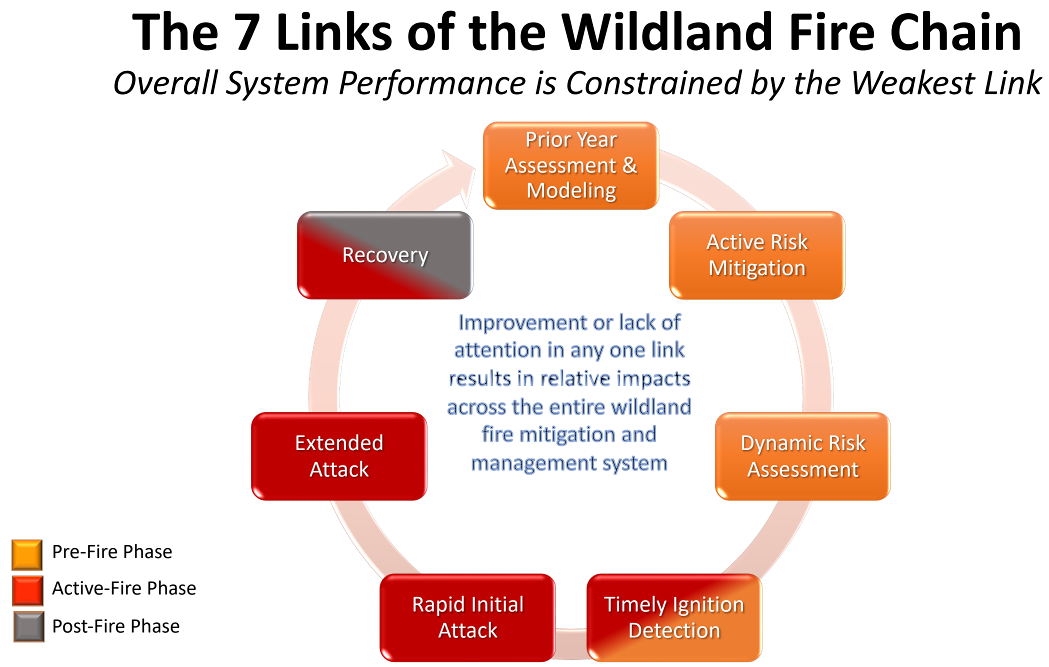


Figure 13. The 7 Links of the Wildland Fire Chain.

Wildland fire chain links associated with the ***Pre-Fire*** *phase include:*

- **Pre-Fire-Year Review and Risk Assessment** – This link includes assessing the previous fire year occurrence and performance with prior year modeling and predictions. This affords opportunities to evaluate confidence levels in current Pre-Fire modeling and predictions and perform valuable updates using last fire year data. This link also encompasses Pre-Fire-Year assessments of hazardous fuel loads and characteristics, long range climate and weather predictions, and known or predicted changes in relevant human activity that could contribute to wildfires and critical values at risk that could alter Pre-Fire-Year strategic planning and resource allocation.
- **Pre-Fire Active Mitigation and Preparedness** – This link encompasses a wide-range of active preventative, mitigation, and preparation activities including, but not limited to active hazardous fuels reduction measures (i.e., prescribed burns), infrastructure, community, and home/business hardening/resiliency activities, wildfire training, equipment readiness preparations, ramping up public service announcements, and exercising available detection, notification, command, and control systems. Shortfalls in managing hazardous fuel levels have been attributed to an increased frequency of megafires [220]. Recognizing this, Pre-Fire hazardous fuels treatments has been the subject of renewed focus by the federal government [221].
- **Dynamic Pre-Fire Risk Assessment** – This link comprises activities that afford fire agencies and managers with critical active intelligence into changing risk conditions enabling them to make timely, data-supported resource allocation decisions in the face of dynamically changing wildfire ignition risks.

Representative activities in this link include assessing changing regional and local fuel flammability measures, shifting fire weather predictions, emergent "red-flag" warnings, and detected changes in human activity (the predominant source of wildfire ignitions). This link serves as a critical bridge between Pre-Fire-Year Review and Risk Assessments and actual Pre-Fire conditions during the fire year.

*Wildland fire chain links within the **Active Fire** phase include:*

- **Timely Ignition Detection** – This link serves as a critical bridge between the Pre-Fire and Active Fire phases. In its Pre-Fire component, timely ignition detection includes activities that ensure an array of systems and methods to provide early detection of wildfire ignitions are in place, ready, and as much as possible networked to provide quality and timely alerts. Representative ignition detection systems serving in this role include utility fault monitors, fixed site visual and thermal sensors, airborne and space-based thermal systems, 911/text/social media reporting systems, smoke sniffers, and lightning detectors. Once a wildfire ignition occurs, this link transitions to the Active Fire phase. The ability of ignition detection systems to provide timely, reliable ignition notifications and precise locations to first responders form key activities in this link.
- **Rapid Initial Attack** – Initial attack (IA) is defined as *"a planned response to a wildfire given the wildfire's potential fire behavior. The objective of initial attack is to stop the fire and put it out in a manner consistent with firefighter and public safety and values to be protected* [222]*."* In 2019, the NWCG Fire Management Board (FMB) included the term "aggressive action to put the fire out by the first resources to arrive," highlighting both the urgency of initial attack and the resource agnostic approach necessary to achieving initial attack goals of putting out the fire [223]. The rapid initial attack link in the wildfire chain forms the first suppression link in the Active Fire phase. This link includes activities that strategically position first responding ground and air assets in response to predicted and dynamically changing wildland fire risk assessments, established procedures for quickly connecting ignition detection alerts and precise locations to first local responders, and policies and methods that afford rapid and prioritized routing for responding initial attack assets. To be fully effective, rapid initial attack capabilities must be able to operate 24/7 in all weather and visual environments safely and effectively. Currently, initial attack first responding assets are, other than in a few specialized units, confined to clear air, daytime conditions. Presently, both helicopter and fixed-wing initial attack assets are constrained during high wind-driven event wildfire ignitions [224], [225]. While drones face similar wind restrictions, there are currently no approved initial attack suppression drones being used in wildland firefighting.
- **Extended Attack** – Extended attack (EA) is defined as "Suppression activity for a wildfire that has not been contained or controlled by initial attack or contingency forces and for which more firefighting resources are arriving, en route, or being ordered by the initial attack incident commander [226]." Because EA operations can extend for long periods of time, the activities necessary to support these operations are more extensive than in IA. As all aerial firefighting operations are intended to support firefighters on the ground, aerial EA operations go beyond direct suppression/retardant operations. Supporting aerial EA activities often include resupply and/or movement of ground firefighters, providing overhead coordination, communications, and connectivity functions, and serving as emergency extraction resources for injured firefighters. As with IA, EA aircraft are for the most part restricted to clear-air visual flight conditions, which generally constrains them to 6-8 hours of operations per 24-hour period but can also result in grounding for multiple consecutive days during large fires. [227], [228].

*The wildland fire chain link associated with the **Post-Fire** phase is:*

- **Recovery –** The recovery link includes critical activities during the latter stages of wildfire containment and extinguishing. These include emergency landscape stabilization to mitigate immediate risks of further damage due to flooding, erosion, watershed contamination, etc. Recovery activities also include long-term planning and actions to promote future landscape resiliency. This can include recommended changes to current local planning and zoning standards and actions to introduce fire-resistant native trees and grasses and measures to prevent encroachment by fire-prone invasive species, such as Cheatgrass [229]. Finally, recovery includes long-term monitoring and outcome measurement of the integrated Post-Fire measures to assess their effectiveness and institute additional actions as required.

5.6 Representative Current and Future Component Activities of the Wildland Fire Chain Links

Each of the seven links in the Wildland Fire Chain can be broken down further into smaller example activity components, as shown in Figure 14. Some of those listed are current activities, while others are desired future state activities that will be discussed in *Sections 5.8 – 5.10*. As the diagram illustrates, the three phases of the wildland fire lifecycle can be broken down to chain links aligned with standard wildland fire functional program terminology (e.g., Initial Attack) and further to representative activities that can be tied to specific program and budget elements.

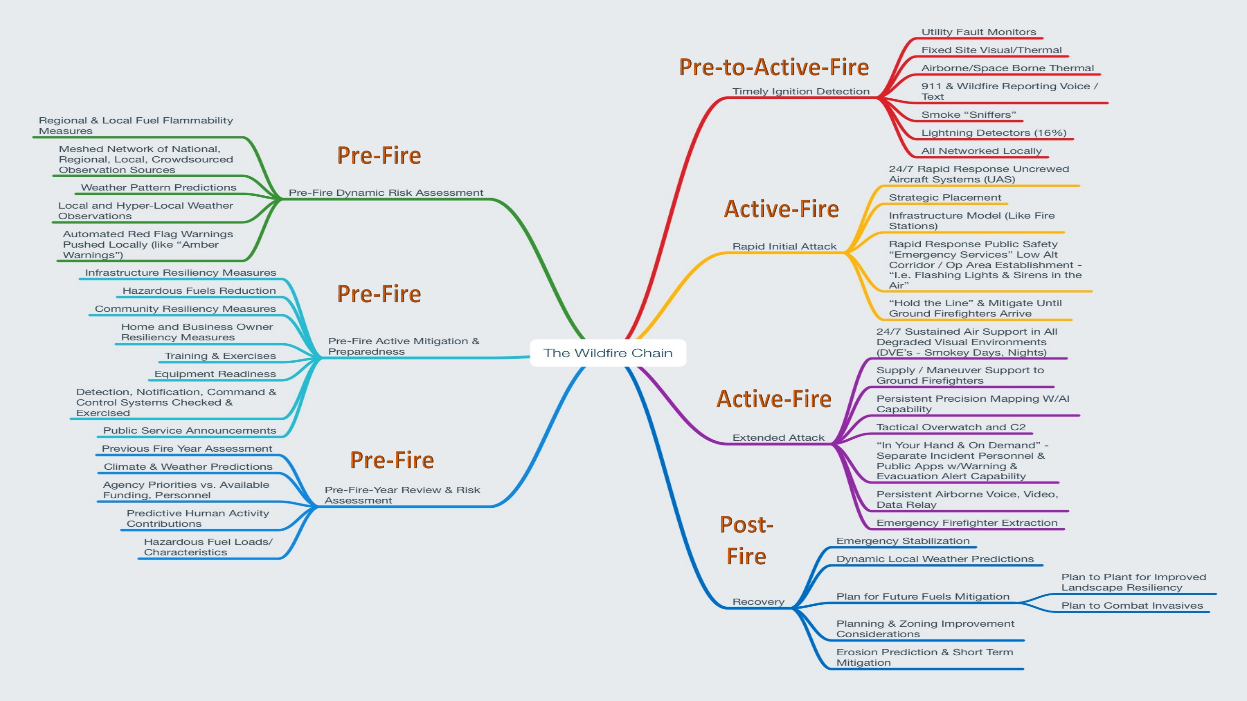


Figure 14. The Wildfire Chain Links and Representative Current and Future Component Activities.

5.7 Technological Themes of the Desired Future State

Before breaking down the wildland fire lifecycle and discussing the future state ConOps in each, it is important to briefly outline and define the technology themes we'll reference and their relevance to the desired future state of wildland fire.

Persistent Connectivity

Wildfires often occur in remote locations and with little warning. Successfully combatting them can require bringing in significant numbers of personnel, ground vehicles, fixed resources, and air assets. These factors, coupled with the inherently hazardous nature of wildland firefighting necessitate reliable, persistent all-weather data, voice, and video connectivity to support the remote sensing future state ConOps. Without reliable, all-environment and terrain connectivity, the full value of supporting technologies cannot be fully realized. Accordingly, this is the linchpin technology for the desired future state.

Persistent Surveillance

Increasingly available commercial and government satellite, sensor-equipped crewed, and uncrewed aircraft, including tactical free-flying/tethered sUAS, and Medium-Altitude and High-Altitude Long Endurance (MALE, HALE) UAS, coupled with fixed and mobile ground assets can be used to improve surveillance of fire regions.

Cooperative Airspace Management to Support Increased Diversity, Safety and Number of Aircraft

Cooperative airspace management systems enable the safe integration and dynamic management of diverse numbers and types of traditional crewed and uncrewed aircraft across a variety of airspace constructs, particularly in those where traditional airspace management and air traffic control services are absent or insufficient for the mission requirements. A high workload activity during fire suppression is coordination of multiple types of traditional crewed and uncrewed aircraft to ensure safe operations. Uncrewed traffic management (UTM) and other current cooperative airspace technology initiatives intended to support UAS, and advanced air mobility (AAM) aircraft could be leveraged to develop a roadmap for automated airspace management technology to reduce this workload and enhance safety.

Navigation, Targeting, Automation, and Remote Piloting Systems to Support Expanded Initial and Extended Attack Support

Previous wildland fire focused flight tests have demonstrated the potential for existing navigation, targeting, automation, and remote piloting technologies to support expanded initial and extended attack and other firefighter support aerial missions [230]. Currently, aerial support to ground firefighters is limited by degraded visual environments (e.g., thick daytime smoke, darkness) to an average of 6-8 hours per 24-hour operating period.

Inclusive Systems Engineering Approach

Systems engineering approaches to complex challenges have a proven track record of being able to identify multiple types of users' needs, map the users' needs into functional requirements, and identify technology and procedure related considerations. Wildland fire involves diverse and complex problem sets and a multifaceted array of direct and indirect stakeholders across all levels of government, industry, academia, and the public.

Data Product and Common Operating Picture Development, Dissemination, and Visualization

The true value of data resides in the products developed from it, the ability to disseminate it to those who need the products and present them in a form that is easily interpreted and immediately useful. Adequately addressing these elements requires a deep understanding of the mission roles and responsibilities of the full range of wildland firefighting personnel. This includes providing incident commanders with visibility into the full range of qualified and available aerial firefighting resources.

Zero Trust and Role-Based Data/Product Access

Data security and aligning the right access to those roles and responsibilities that require it are both important to wildland firefighting. Zero Trust (ZT) is a security framework that requires all users, whether inside or outside the organization to be continuously validated for access. ZT can also assist agencies and organizations in implementing role-specific access to data and data products to ensure the right data gets to the right people who need it in relevant-time. This would be particularly valuable in the wildland fire mission space where multiple Federal, State, Local, Tribal, commercial, and private entities and are working together to combat a wildfire, providing critical resource availability and situational awareness to incident commanders.

Edge-Compute

Increasingly, more data is being collected at edge where the mission is occurring. Commensurate with this are growing demands for data and derived products for consumption by operators working at the edge. Edge-compute involves increasing the processing power and storage for data collected at the edge for use where it was collected. Edge compute can also serve to mitigate the detrimental effects of increasing demands on existing and future data networks. As the number of remote sensors in wildfire continues to grow, particularly on the edge, the demand for edge-compute by those in the field will increase as well.

Edge-to-Cloud

Designed to bring the cloud experience to an organization's apps and data, regardless of where they reside. Edge-to-cloud supports the growing demand for real-time data supported decision-making, especially at the edge. Edge-to-cloud connects the far-edge where data is increasingly generated and consumed to the near-edge, where mobile data centers can provide incident commanders with low latency, relevant-time decision support products, while the cloud enables the full measure of AI/ML modeling updates.

AI/ML

Artificial intelligence generally refers to processes and algorithms that can simulate human intelligence, including mimicking cognitive functions such as perception, learning and problem solving. Machine learning (ML) is a type of artificial intelligence (AI) that allows software applications to become more accurate at predicting outcomes without being explicitly programmed to do so. AI and ML can help address the analytic scaling challenges that come with the exponential growth of collected data from remote sensors. AI can enhance low latency, high fidelity decision support, while ML enables supporting algorithms to learn and improve over time. AI/ML models could be trained in a build-up approach from specifically selected small prescribed fires up through managed, Type III, Type II, and Type I wildfires, striking a balance between data collection volumes and useful output.

Federated Learning to Support Inclusive and Adaptive Remote Sensing

Federated Learning (FL) is a method to train Artificial Intelligence (AI) models with data from multiple sources while maintaining anonymity of the data thus removing many barriers to data sharing [231]. FL overcomes many of the traditional challenges experienced in gaining access to and leveraging the power of disparate remote sensing data from other Federal, State, Local, Tribal, and Territorial agencies as well as commercial and private parties supporting or in the vicinity of wildland fire operations. FL recently proved its value during the COVID-19 pandemic, enabling the updating of critical predictive AI/ML models while maintaining the privacy of supporting medical data [232], [233]. FL also reduces network bandwidth demands and accelerates the time to value and fidelity of updated algorithms.

Assisted and Autonomous Vehicles and Machines

As we have seen in the automotive industry, assistive and autonomous technologies (i.e., vehicle proximity alerts, automatic collision avoidance braking/steering inputs, etc.) can increase safety and reduce operator workload. Vehicle and aircraft accidents that occur with troubling regularity in the hazardous wildland fire mission space could likely benefit from these technologies, either assisting human operators or enabling them to be removed from the most hazardous mission environments.

Digital Twins and Advanced Modeling and Simulation

A digital twin is a virtual model designed to accurately reflect a physical object or scenario. Digital twins derived from data gathered during real events provide unique opportunities for injecting alternative conditions and operational approaches that enable new technologies and operational methods to be modeled in a mission representative simulation. They can also be used to identify critical decision inflection points that were key to experienced outcomes.

Outcome Measures of Effectiveness for Pre-Fire Planning and Active Fire and Post-Fire Assessments

Outcome measures of effectiveness are key in assessing the impact of current and altered programs and methods, in continually evaluating present performance, and as planning factors in future acquisition and operational planning. Advances in technologies and methods for determining outcome measures could be used to support more efficient and effective wildland fire mitigation and management operations.

Organizational and Cultural Considerations and Adaptations Necessary to Successfully Integrate Current and Future Technologies with Consistent and Accepted Standards

Previous attempts to integrate new technology in the wildland fire space have failed to fully understand and work within the organizational and cultural realities of the wildland firefighting community and its complex array of direct and influencing stakeholders.

Human Factors Risk Assessment and Mitigation

Human activity is responsible for 85% of all wildland fires. In-depth assessments of static and dynamic human activity risks and derived mitigations could result in better preventative actions to mitigate wildland fire risk and/or loss.

5.8 Pre-Fire

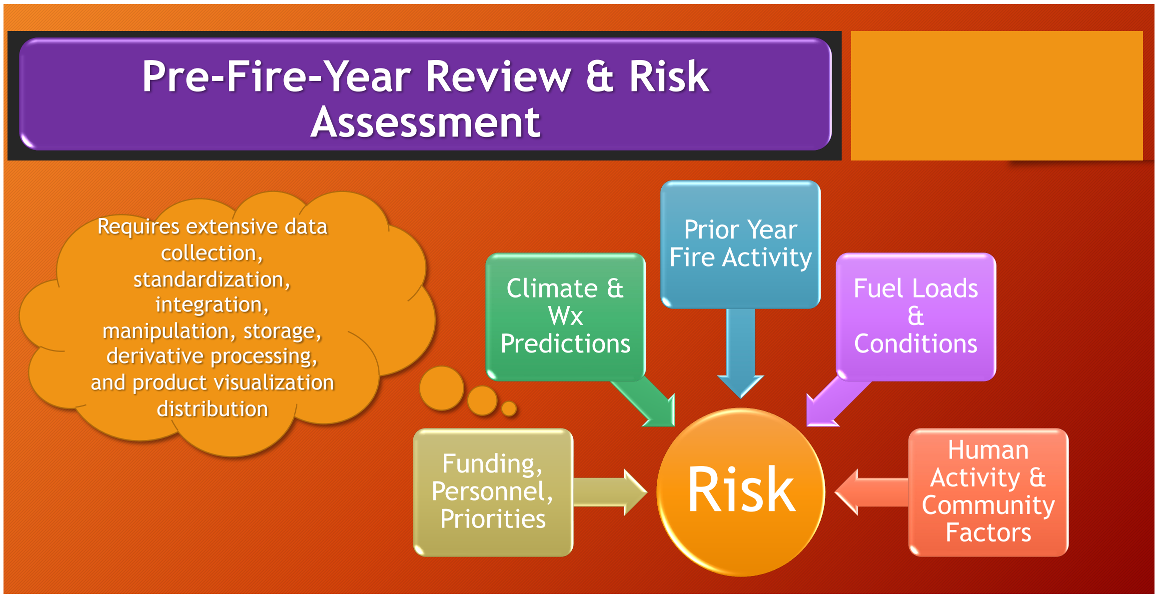
5.8.1 Pre-Fire-Year Review and Risk Assessment

Inherent to the philosophy of continual improvement is the ability to effectively review and learn from previous process outcomes and the results of implemented technological, organizational, and operational changes (Figure 15). Currently, wildland fire agencies derive and deliver a range of useful predictive wildfire risk assessment products related to fire weather and climate, fuels and fire danger, and fire activity and firefighting asset intelligence [234]. However, these products presently take the form of published official reports which are often provided in briefings to wildland fire managers; they are not digitally integrated into dynamic assessment and risk models that offer opportunities to compare present results with previous predictions [235], [236]. They are also not connected with data from ongoing initiatives that have brought fire forecasting into the wild [237]. As a result, there is a structural gap to fully leveraging the potential value of this data in assessing the efficiency and effectiveness of the prior years' operations and the efficacy of implemented changes.

In the desired future state, data collected from the previous year's wildland fires, hazardous fuels treatments, and other risk management activities will be incorporated into sustainably updated data sets. Currently, these data sources are scattered across agencies and programs, creating training and operational inefficiencies. The wildland fire management community needs seamlessly integrated programs and equipment to view and understand relevant data, those which do not require extensive training for scaled, cross-jurisdictional use and, in turn, supports timely collaborative decision making. To accomplish this planning, wildfire management agencies also need current, reliable, comprehensive, and regularly updated data sets that include information about cities, counties, and state governments. Also essential is information on commercial oil and gas pipelines, electric transmission lines, building footprints, roads, structures, water and power infrastructure, fire weather, fuel moisture, vegetation, etc. [238]. Organizationally, collaboration on Pre-Fire-Year Reviews and Risk Assessments are also hampered by a lack of collaboration across all major stakeholders. Participants at a 2021 interagency wildfire management workshop hosted by NASA noted that the National Wildfire Coordinating Group (NWCG), the umbrella organization responsible for wildland fire training, certification, and equipment standards could benefit from expanded and more formal partnerships with the Department of Defense (DOD) and NASA, both of which could provide access to physics-based modeling, advanced computing methods, and data collection and distribution techniques [239]. Participants in this workshop also noted that current wildland fire lessons learned are largely retrospective, captured over varying time scales, and heterogeneous, all of which hampers the forward-looking analytical value of this data [240].

Supplemented by data from earth-scale climate models, improved vegetation data maps, and hyper-local fire weather predictions, these integrated data sets will support a range of improved AI/ML-supported models [241], [242], [243]. These increasingly intelligent models will provide wildland fire management stakeholders with critical prior-year performance information, serve to identify the value of implemented changes, and highlight gaps and opportunities for improvement in the coming fire-year, all in the Pre-Fire phase [244]. Also, extensive and detailed data collected from selected large and megafires will be used to build digital twins of these significant prior-year events. As has already been demonstrated in industry, these digital twin models can be used to assess past performance, identify necessary adjustments, better predict the pace and progress of future events, and model the potential outcome of inputted variations in conditions, capabilities, available resources, management decisions, and workflows through iterative interactive simulations [245], [246].

Leveraging these large, collected data sets, digital twins, and AI/ML-supported models, factors like updated climate and long-range weather predictions, actual vs. predicted fire-year activity, fuel loads and conditions, agency funding, personnel, and asset status, and revisions to expected human activity and wildland urban interface (WUI) changes can be evaluated to provide wildland fire agencies and managers with more precise Pre-Fire-Year Review and Risk Assessments.



Pre-Fire-Year Review & Risk Assessment

Requires extensive data collection, standardization, integration, manipulation, storage, derivative processing, and product visualization distribution

Climate & Wx Predictions

Prior Year Fire Activity

Fuel Loads & Conditions

Funding, Personnel, Priorities

Risk

Human Activity & Community Factors

Figure 15. Pre-Fire-Year Review & Risk Assessment in the Desired Future State.

This vision of the desired future state is supported by the February 2023 President's Council of Economic Advisors on Science and Technology (PCAST) report to the President. Specifically, the report makes a recommendation to "accelerate improvement of predictive wildfire modeling tools by expanding research community access to archived satellite data from defense and other government sources [247]."

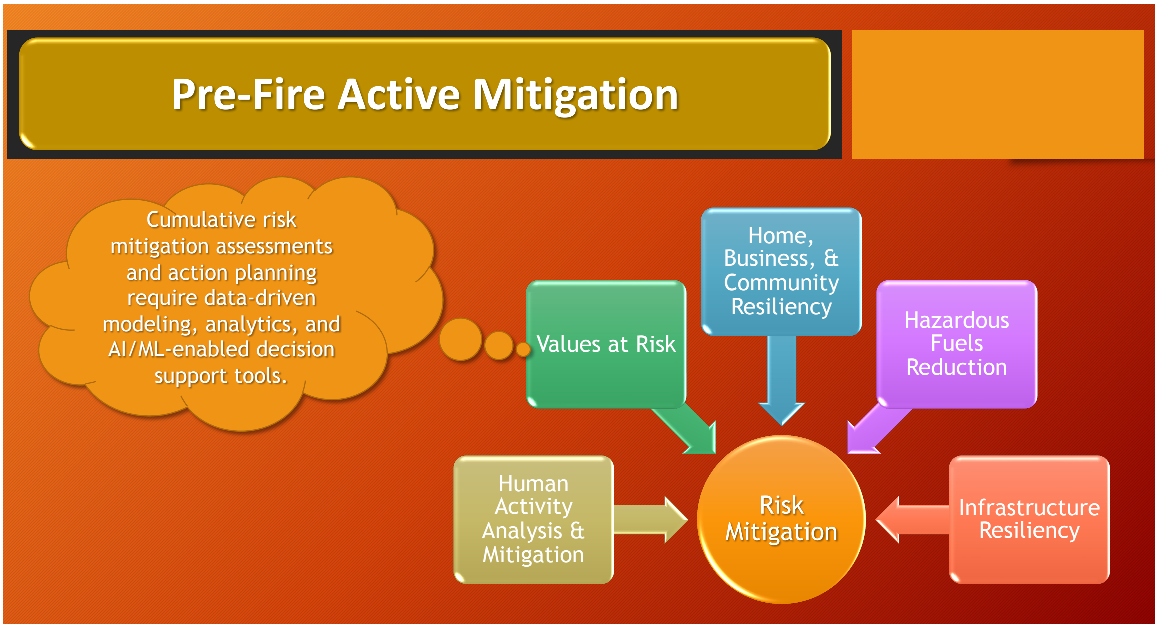
5.8.2 Pre-Fire Active Mitigation

As with any adverse, potentially damaging event, mitigating the risk of a wildfire occurrence or moderating its intensity should an ignition happen is always preferrable (Figure 16). As we have learned in the previous section, Current State of Wildland Fire in the U.S., decades of inattention to Pre-Fire Active Mitigation measures and an over-focus on the quick suppression of every wildfire ignition have resulted in an unprecedented period of increasingly ferocious and destructive megafires that have resulted in staggering economic and human losses. In the desired future state, there will be a renewed focus on Pre-Fire Active Mitigation, consistent with historical traditions like cultural burning, while leveraging significant and available advances in fire tech [248], [249]. The desired future state of Pre-Fire Active Mitigation will also encompass an integrated, data, modeling, and AI-ML supported approach to target the best available mitigation decisions for areas of the highest wildfire risk.

Pre-Fire Active Mitigation can take many forms. Traditionally, the measure that gets the most attention has been fuel treatments to reduce hazardous conditions in high-risk areas [250]. Among the many methods for conducting fuel treatments, its widely recognized that prescribed burns are one of the most efficient and effective measures at reducing potentially hazardous fuel loads [251]. However, in recent decades instances of prescribed burns breaking containment to become destructive wildfires and increased public and medical concerns over the potential adverse health effects of smoke from prescribed burns have resulted in significant curtailment or even widespread and long-lasting bans on prescribed burning [252], [253]. The desired future state seeks to address these concerns through the integration and application of new and emerging technologies. One such technology was recently demonstrated by Pacific Gas and Electric (PG&E). A remote-controlled "BurnBot" capable of controlling the rate of the burn, greatly reducing the resultant smoke emissions, and providing post-burn extinguishing services was successfully tested under high-voltage transmission lines where the threat of and uncontained prescribed burn and the potential electrical arcing through traditional levels of smoke from prescribed burns would have otherwise prevented this fuels treatment [254]. Another prescribed burn technology envisioned for the future state is the increased use of aerial ignition drones. Originally developed by the U.S. Department of the Interior in partnership with the University of Nebraska at Lincoln in 2016, aerial ignition drones have seen increasing use in prescribed burns [255]. Since then, DOI and USFS aerial ignition UAS have improved firefighter safety by replacing the need for aerial ignition helicopters in many of these missions; helicopter accidents in aerial ignition have resulted in 6 fatalities since 2005 (the latest in 2019) [256], [257]. In 2016 at the Asia-Pacific Aerial Firefighting Conference in Australia, DOI briefed the results of its aerial ignition development, testing, and mission integration process and first proposed the use of swarms of aerial ignition equipped drones to mitigate the challenges of traditional prescribed burns where the length of the burn may take it outside the window of favorable weather conditions [258]. The desired future state envisions an integration of automated ground and aerial ignition vehicles, working in concert to mitigate the risk of prescribed burn breakouts and minimize generated smoke. The automated ground burn bots would conduct perimeter burns where loss of containment and smoke concerns would be greatest. Additionally, they would conduct "checkerboard" burns across the intended burn area, building fire breaks in support of the next phase. Once complete, multiple aerial ignition drones would conduct burns on the remaining unburned "squares," enabling quick, limited burns across the remaining burn area that further mitigate the risk of an uncontained burn and the exposure time to smoke.

Mechanical removal of hazardous fuels is another traditional means of reducing the pre-fire risk of wildfire ignition and mitigating the intensity of potential future wildfires in the treated areas [259]. Mechanical treatment can range from pruning lower tree branches, brush removal, creation of fire breaks, to the large-scale thinning of trees across targeted areas. Mechanical treatment can be accomplished on its own or in concert with prescribed burning and can be used ahead of prescribed burning as a hazard reduction measure for reducing the risk of a prescribed burn breaking containment. Mechanical treatments tend to take longer and are generally more labor intensive and costly than prescribed burning. One way to reduce mechanical treatment costs and increase their efficiency in the future state would be to employ ground robotics. Such equipment is already in use in the logging industry where it has served to increase productivity, improve worker safety, and reduce cost [260], [261].

Having empirical evidence of the effectiveness of landscape level fuel treatments has also challenged increased adoption of prescribed burns and is recognized as a current capability gap [262]. In the desired future state, the increased use and integration of persistent space-based, airborne, and earth-based remote sensors will gather the data necessary to develop and support AI/ML models and decision assist tools that will be able to measure hazardous fuel loads and quantify the fuel risk reduction following treatments [263]. These future technological advances in determining the highest hazardous fuel risk areas and quantifying the effects of treatments are particularly critical when considering the large gap between the number of high-risk acres and the amount agencies are able to treat each year. As an example, a December 2019 report by the U.S. Government Accountability Office (GAO) cited agency reports that while there were about 100 million high-risk acres necessitating treatment, they were only able to treat about 3 million in FY2018 [264]. While significant federal funding has been applied to increase the treatment of hazardous fuels, they are insufficient to close the gap completely, necessitating an emphasis on other Pre-Fire Active Mitigation measures in the desired future state [265].



Cumulative risk mitigation assessments and action planning require data-driven modeling, analytics, and AI/ML-enabled decision support tools.

Figure 16. Pre-Fire Active Mitigation.

Consistent with the National Cohesive Wildland Fire Management Strategy, Addendum Update 2023, the desired future state of Pre-Fire Active Mitigation will also include examination and mitigation of values at risk and home, business, community, and infrastructure resiliency, leveraging the same technologies to support improved hazardous fuels reduction assessments and decision making in these areas. New to the desired future state in Pre-Fire Active Mitigation will be the emphasis and approach to assessing human activity risks and possible mitigation measures.

As we learned in *Section 4: Current State of Wildland Fire in the U.S.,* nearly 85% of all wildfires are the result of human activity [266]. General human-caused wildfire focus areas include [267]:

- Arson
- Debris and open burning
- Equipment and vehicle use (e.g., dragging trailer chains, parking where hot engine/exhaust components ignite grass fires, etc.)
- Firearms and explosives use.
- Fireworks
- Misuse of fire by minors
- Power generation, transmission, distribution
- Railroad operations and maintenance
- Recreation and ceremony (including campfires and outdoor grills)
- Smoking
- Electric fences
- Glass refraction – magnification
- Spontaneous combustion
- Structure fires

In that section we were also exposed to the Wildfire Behavior Triangle (Figure 1, and again in Figure 17), which has been around for decades and has been used to describe the three components that govern wildfire behavior [268].

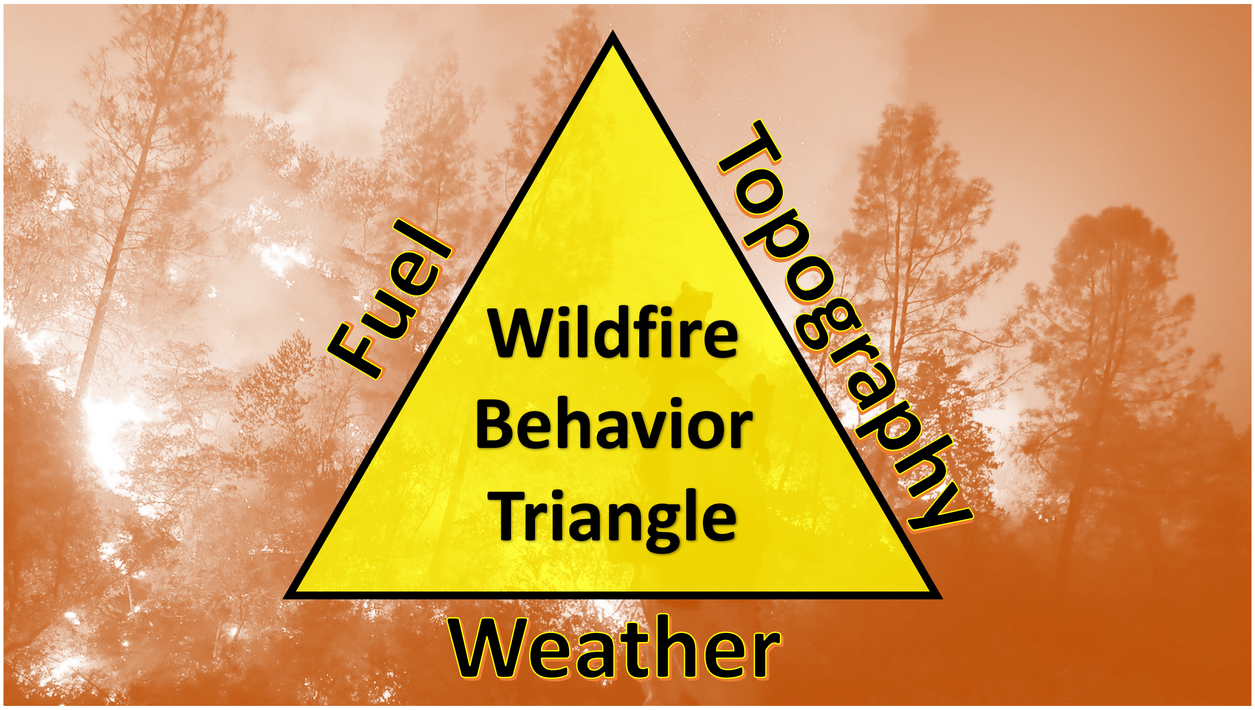


Figure 17. The Traditional Wildfire Behavior Triangle.

While this construct has served the wildland fire community well in the past, the nature, contribution, and impact of human activity on wildfire behavior necessitates we update this construct in shaping the desired future state. Human activities related to wildland fire are traditionally thought of as those activities that result in wildfire ignitions [269]. However, human activities that contribute to wildfire behavior can also include:

- Local planning and zoning
    - Tightly grouped homes can form fuel ladders that promote the rapid spread of wildfires, particularly in wind-driven events.
    - Evacuation planning and identification of potential chokepoints and routes susceptible to blockage from downed powerlines, trees, etc.
    - Hardened building requirements
    - Defensible space requirements
- Power generation, transmission, distribution, and contingency planning
    - Above-ground lines
    - Aging infrastructure
    - Proximity to evacuation routes
    - Connection to warning and evacuation systems.
    - Policies for shutting off power during red-flag warnings, high wind events, notification of power faults, and wildfire ignitions.
- Seasonal human activity spikes, special events.
    - Dragging trailer chains sparking ignitions along highways over long-holiday weekends
    - Campfire ignitions over peak summer holiday periods
    - Fireworks on the 4th of July
    - Firearms use in preparation for or during hunting seasons.
    - Special events (e.g., gender-reveal, cultural, remembrance events, etc.)
- State, regional, local government wildfire risk assessments, training, and exercises.
    - Aligned with the known topography, weather, and fuel conditions as well as known human-caused baseline and dynamic community risks (e.g., seasonal tourism, special event impacts).
    - Emergency and alert systems tested, validated, first responder and community training, drills.
    - Access to and incorporation of dynamic weather, fuel, infrastructure condition, human activity risk factor information to support active updates to local risk assessments.

Increasingly, the staggering losses experienced during megafires are a direct result of factors that are a direct result of human planning and decision-making activities. The 2018 Camp Fire and the 2023 Maui fire serve as stark examples of this. In the Camp Fire, a nearly 100-year-old electrical transmission line (mean life expectancy was 65-years) was identified as the ignition source [270]. Escape routes were limited, soon after the local 911 dispatcher was inundated with reports of the fast-moving fire, phones were knocked out. Unprepared for the speed of the fire spread (80 football fields a minute), in only 4-hours, 18,800 structures (nearly 14,000 residences) were destroyed and 85 people lost their lives. Tragically, the recent Maui fire bears shocking similarities; few escape routes, power line ignitions with no established process to secure power during high-wind/red-flag events, phones knocked out, insufficient warning systems, underestimated risk, lack of preparation, training, and exercises, and local emergency responders quickly overwhelmed [271]. The human activity related to the Maui fires was further reinforced when it was discovered that many of the electrical power distribution lines there were uninsulated, which resulted in numerous ignition points of origin as the lines were blown by the high winds into nearby dry standing vegetation or knocked to the ground [272]. Videos from that fire showed those bare powerlines igniting an unnatural line of flame [273]. Had the power lines been insulated as they are in most of the U.S., the ignition opportunities would have been far less.

Given our increased understanding of far-reaching and complex nature human activity can have in influencing wildfire behavior and its attendant economic and human losses, in the future state we propose updating the traditional wildfire behavior triangle to a wildfire behavior diamond (Figure 18).

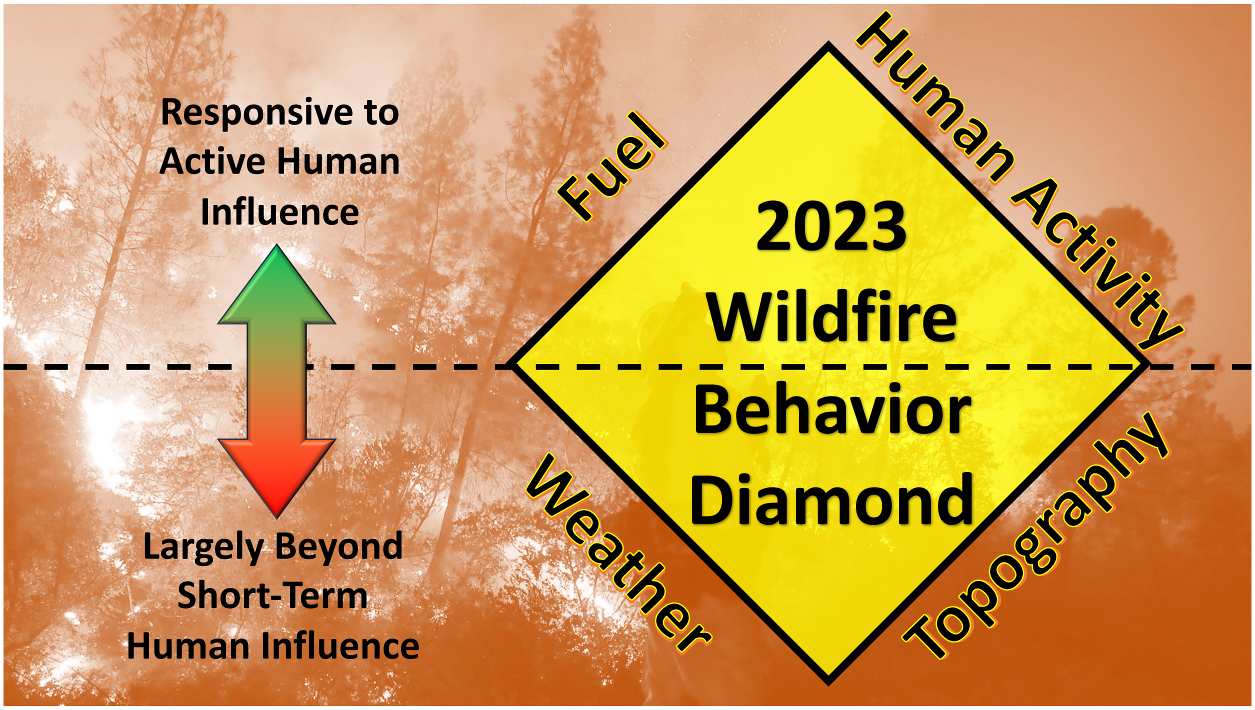


Figure 18. The 2023 Wildfire Behavior Diamond.

The 2023 wildfire behavior diamond builds on the traditional wildfire behavior triangle. While it includes weather and topography from the wildfire behavior triangle, it further differentiates them as being largely beyond short-term human influence; important factors that must be considered in risk assessments and planning, but largely outside our direct control. Similarly, it identifies fuel as a wildfire behavior factor that is very much within our ability to influence (e.g., fuel treatments, invasive species management, etc.). While structural and human-planted vegetative fuels have always been part of the fuel leg of the wildfire behavior triangle, this leg failed to capture the many other elements of human activity that have repeatedly contributed to the nature and extent of wildfire behavior, particularly in recent, costly megafires. In the desired future state, the integration of the full range of potential human activity contributions to wildfire behavior will expand the reach and improve the outcome of Pre-Fire Risk Mitigation activities.

5.8.3 Dynamic Pre-Fire Risk Assessment

There is a well-worn axiom that “no plan survives first contact with reality.” Another, specifically related to wildland fire is that “all wildfires are local for those who live there.” This is certainly true in wildland fire risk assessments. While the Pre-Fire-Year Review and Risk Assessment is a critical link in the wildfire chain that can set the stage for success or failure during the fire year, its value diminishes as the factors on which those assessments were based experience natural and often interconnected variations. While there are current products that integrate a range of contributing observational factors in fire potential model to provide a 7-Day Significant Fire Potential Outlook, these products are regional in nature, providing limited utility to local governments and land managers [274]. In the desired future state, Dynamic Pre-Fire Risk Assessments will provide continuously updated, hyper-local wildfire risk assessments. These dynamic risk assessments will enable governments, businesses, and the public to implement active group and individual preparation and risk mitigation measures in response to changing conditions. Characteristics of desired future state Dynamic Pre-Fire Risk Assessment systems include (Figure 19):

- Access to a diverse array of national, regional, and local observational data (satellite, airborne, ground-based) using federated learning methods that enable the use of proprietary and private data to update AI/ML risk assessment models without having to decrypt the data.
- Incorporating far-edge, near-edge, and cloud computing capabilities to reduce network requirements, cut latency, and improve time to value for AI/ML decision support models and tools.
- Networked to automated detailed and hyperlocal wildfire risk warning, alerting, and first responder systems to support timely human-initiated risk mitigation measures.

- Connected to automated utility safety measures to provide immediate safety mitigation in the face of rapidly changing local risk conditions.
- Role-based product derivation and distribution to provide the right parties with the right information at the right time and to avoid the detrimental effects of information overload.
- Greater inclusion of regional and local government participation and influence. Local community first responders often represent the first units on the scene in a wildfire and the damage to homes, businesses, and communities is decidedly local. In the desired future state there will be increased collaboration with regional and local stakeholders across all links of the wildland fire chain, including the important Dynamic Pre-Fire Risk Assessment link.

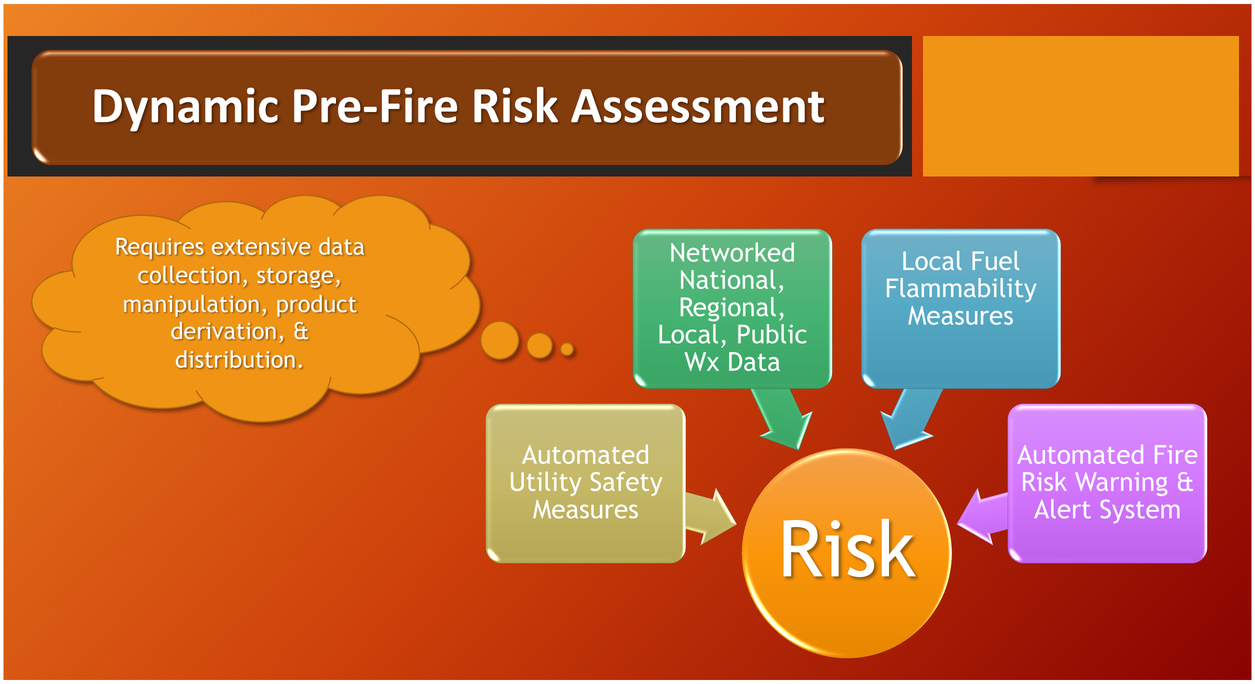


Figure 19. Dynamic Pre-Fire Risk Assessment.

5.9 Active Fire

5.9.1 Timely Ignition Detection

Ignition detection represents the critical bridge between the Pre-Fire and Active Fire phases. While every fire starts small, the time between ignition and detection can be a significant contributing factor in the eventual size and destructive power of the resultant wildfire. As with assessing the risk of wildland fire occurrences, timely ignition detection is best accomplished through an integrated system of complementary technologies. In the desired future state, an integrated ignition detection system will include the following components (Figure 20):

- Utility fault monitors
    - Aging and wind-vulnerable utility generation, distribution, and transmission infrastructure has served as the ignition source in several of the most destructive wildfires in the U.S. (e.g., 2018 Camp Fire and 2023 Maui Fire)
- Space-based and airborne (traditional crewed aircraft, MALE, HALE, sUAS) thermal sensors
- Fixed site government, commercial, and private visual and thermal sensors
- Smoke "Sniffers"
    - Strategically placed in high-risk areas, equipped with grid-independent power sources (e.g., solar, battery, wind)
- Lightning detectors
- 911, social media, and dedicated wildland fire reporting voice, text, and data channels.

    - Humans are often the first to detect and report wildfire ignitions.

While many of these components exist today, the desired future state requires that they are networked into an ignition detection system. Requirements of this future system would include:

- Persistent connectivity from all edge nodes.
- Far-edge compute capabilities to mitigate the data network ingest loading back to the near-edge and cloud compute locations.
- Data standards and federated learning protocols that promote data sharing while preserving data security and privacy.
- Data storage, analytics, and product development.
- AI/ML modeling to progressively reduce false positives and detection alert delays through continual learning.
- Role-based product derivation and distribution to requisite stakeholders at every level, providing the right product to the right position/person, at the right time.
    - Public access could be through current mobile phone-based State/Local emergency alert systems.
- Networked connectivity to appropriate alerting and automated infrastructure action functions.

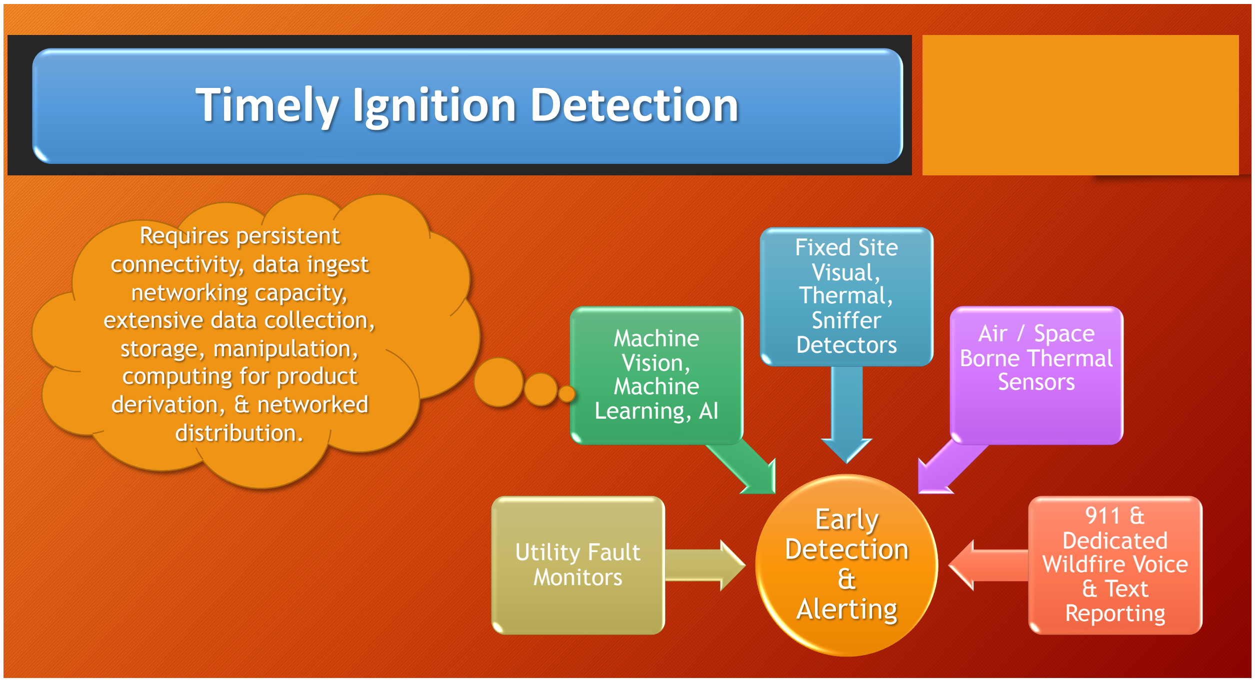


Figure 20. Timely Ignition Detection.

5.9.2 Rapid Initial Attack

Initial attack (IA) is defined as "an aggressive action to put the fire out by the first resources to arrive, consistent with firefighter and public safety and values to be protected [275]." Among the guiding principles of the National Cohesive Wildland Fire Management Strategy is that "safe aggressive initial attack is often the best suppression strategy to keep unwanted wildfires small and costs down [276]." Historically, initial attack has enjoyed a 98% success rate of containing new fire starts within the first 24-hour operational period [277]. While this is an impressive statistic, it also means that 2% of all new fire starts result in the increasing number of large, costly, and deadly megafires that have occurred in recent years [278]. These 2% of wildfires account for 97% of the billions in annual firefighting costs and millions of total area burned each year [279]. Among the contributing factors that influence whether a new fire start becoming a large or megafire are topography, fuel type, fuel moisture level trends, and recent weather factors, such as wind [280]. Recent studies have also shown that the time between initial ignition and the arrival of initial attack resources can have an adverse impact on containing wildfires during the first 24-hour operational period. A 2009 Australian study by the Bushfire Cooperative Research Center developed models based on data from 500 fires at a range of locations in Australia between 2004 and 2008. Resultant probability graphs from this report (Figures 21 and 22) illustrated a direct relationship between the time between initial ignition detection and first attack [281].

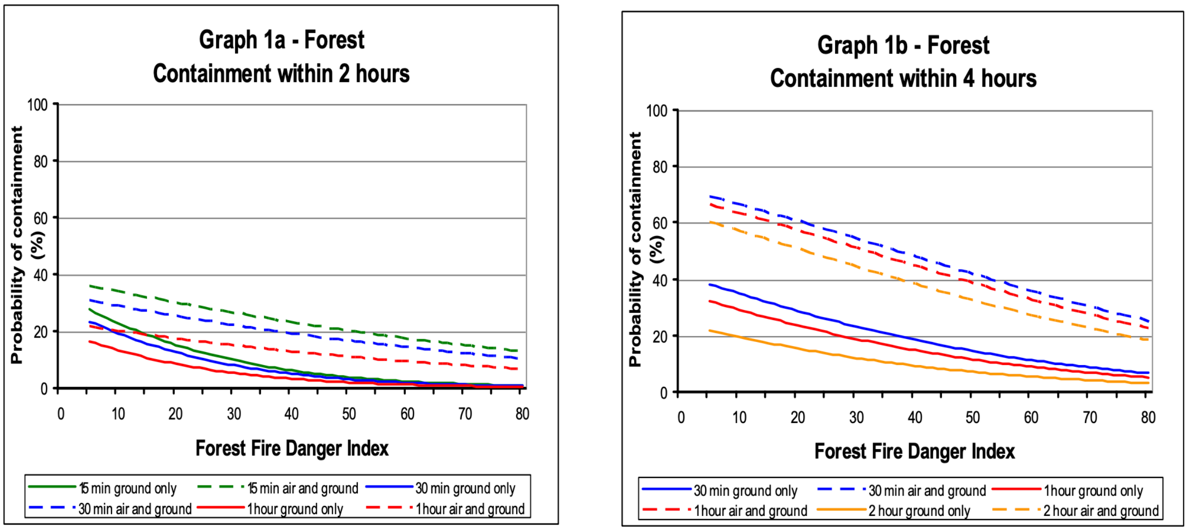


Figure 21. Probability of Containment Within 2 and 4 Hours Based on Time from Ignition to First Attack [281].

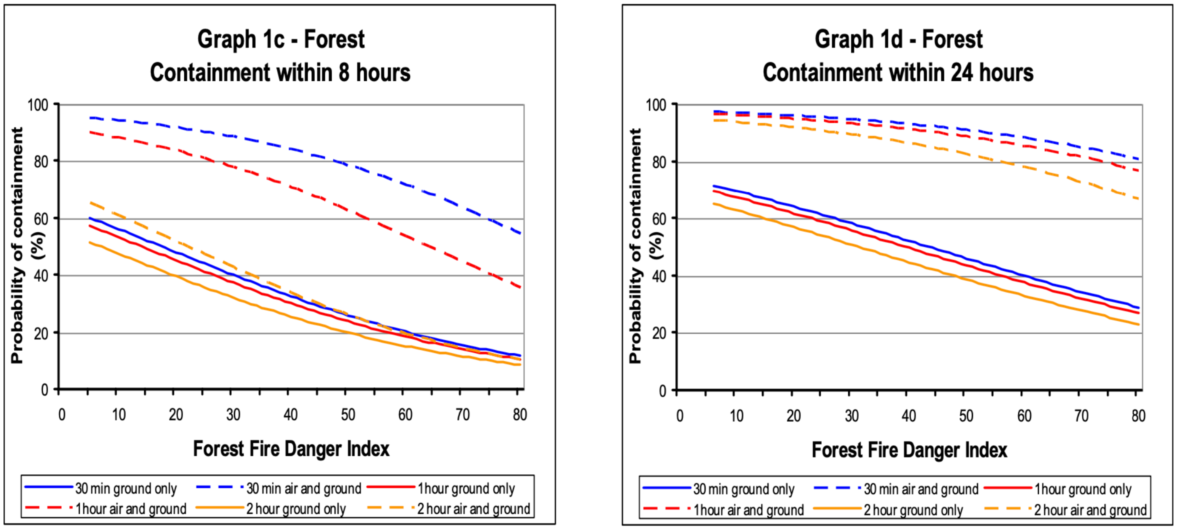


Figure 22. Probability of Containment Within 8 and 24 Hours Based on Time from Ignition to First Attack [281].

The Australian study not only demonstrated a clear link between probability of containment and the timeliness of initial attack resources, but also reinforced the value of integrated ground and aerial firefighting operations in increasing the probability of containment. While simultaneous arrival and coordination of ground and aerial firefighting resources in initial attack is the ideal, there are several factors that often results in either ground or air resources being the first to arrive on scene. As is also depicted in the above probability graphs, having one of the two initial attack resources onsite is better than none. Ground resources are often the first to arrive at fire starts that occur within easy access to established roadways and close to their local stations. However, fire starts that occur far from available road infrastructure and/or in steep terrain make it challenging for ground resources to safely respond in a timely manner, particularly at night when the chances for injury and entrapment are historically higher. Likewise, rapid initial attack response by traditional aerial firefighting resources can be affected by high winds and/or degraded visual environments (DVE's, e.g., blowing dust, smoke, darkness). A 2017 study by the DOI Office of Aviation Services (OAS) of 2015-2017 fire start data examined this phenomenon, looking at the relationship of fire discovery times on the timeliness of initial attack aerial firefighting support. It found that nearly 20% of all fire starts that occurred during this period happened outside the hours of traditional air support (Figure 23) [282].

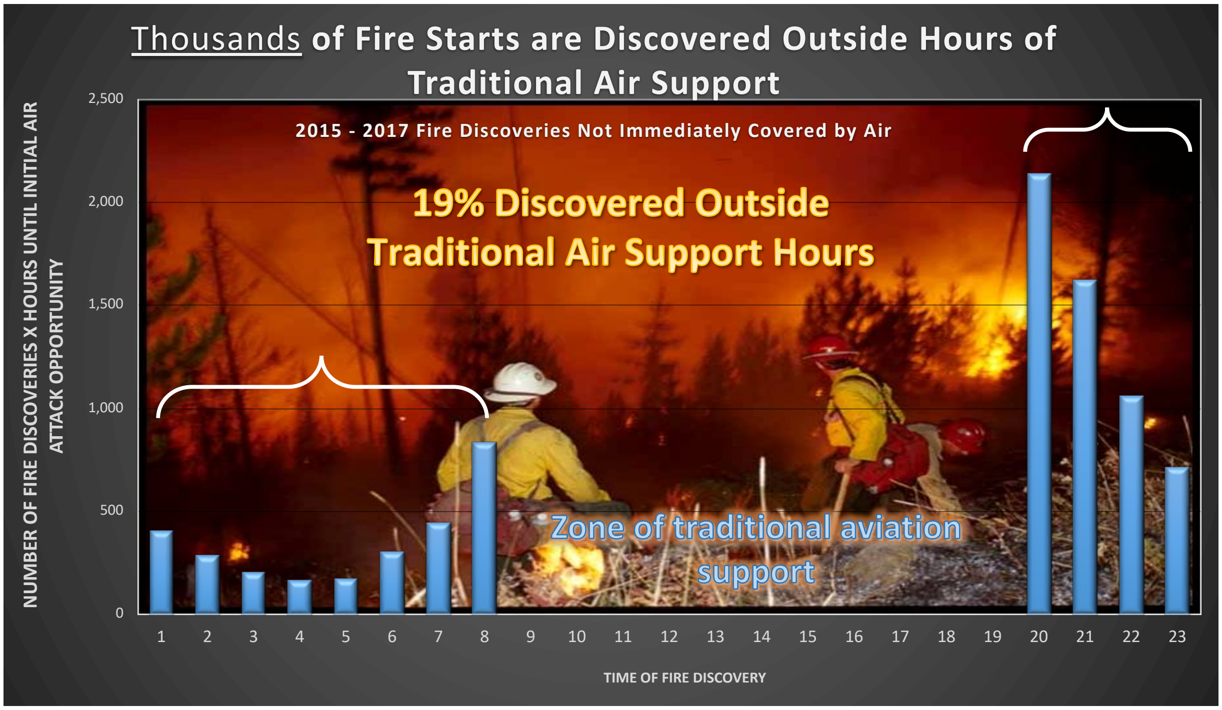


Figure 23. Relationship of Fire Discovery Times on the Timeliness of Aerial Firefighting Support.

Additionally, it was discovered that 66% of these fire starts occurred between the traditional end of flight operations (sunset) and midnight, giving them the greatest opportunity to grow unchecked by initial (and extended) aerial resources.

The desired future state of initial attack will leverage current and developing technologies to address current challenges in achieving rapid initial attack on the 2% of wildfire starts that result in 97% of the annual cost and loss. As we've seen from the data, current traditional crewed aerial firefighting aircraft are unable to provide support in DVE's. While the use of night vision devices (NVD's) has provided some night aerial firefighting capability, they are useless during daytime DVE's (blowing dust, smoke) and require significant equipment and initial and recurring training costs to ensure safety and proficiency [283], [284]. These NVD-equipped crewed helicopters also remain constrained by the same high wind limitations that can prevent initial attack operations during wind-driven ignition events. To address these challenges, the desired future state will incorporate a system of rapid-response uncrewed aircraft systems (UAS) capable of safely and effectively providing rapid initial attack response in direct support of ground firefighters or in advance of their arrival on scene to reduce their risk and increase the probability of containment. Characteristics of the desired future state of rapid aerial initial attack capabilities include (Figure 24):

- Development of a 24/7, All-Weather, Safe and Effective Rapid-Response Initial Attack Aerial Capability
    - Leverage previous DOD development of the KMAX remotely piloted full-scale, FAA certificated helicopter, later tested by DOI in 2014 and 2015 in wildland fire representative mission demonstrations.
    - Examine other ongoing initiatives for developing DVE capabilities for traditional crewed aircraft using multiple aircraft-mounted sensor technologies that enhance situational awareness and deliver a real-time, clear, synthetically adapted image to the pilot [285].
    - For potential UAS solutions incorporate onboard sensors (e.g., mid-wave infrared, LiDAR, etc.) that enable the remote operator to visualize the fire, ground, and obstacles.
    - Use precise positioning through GPS, detailed digital terrain maps, radar/laser altimeters, and related technologies.

  - Provide the ability to fly to potential fire ignition locations via programmed flight paths (vice hand-flown).
  - Incorporate onboard electronic ID systems to ensure visibility with FAA and other aircraft.
  - Highly integrated with the future collaborative low altitude airspace system, enabling quick alerting and clearance of flight path with air traffic authorities.
  - Equipped with Vehicle-to-vehicle (V2V) communications for all participating aircraft to enable multi-initial attack UAS operations and detection, control, and collision avoidance (C&CA) with other UAS and crewed aircraft; part of a layered system of detect and avoid technologies. The precedent for mandating the use of government-furnished avionics in wildland fire is the Automated Flight Following (AFF) system that is required on all USFS and DOI-owned and contracted aircraft [286].
  - Incorporates an initial suppressant payload capability comparable with current Type III initial attack helicopters.
  - Designed with the ability to safely launch, operate, and recover in high and gusty wind conditions 24/7.

- Strategic Placement
  - Autonomous initial attack units strategically placed based on the results of a thorough risk assessment of local values at risk, human activity and infrastructure ignition risks, fuel type, topography, etc.
  - Siting plan comparable to traditional fire station model; an element of local public safety infrastructure.

- Automated Integration with Local Wildfire Ignition Detection Networks
  - Enabling reduced response times and increasing the probability of containment.

- Close Coordination with FAA to Develop Rapid Response Public Safety Low Altitude Corridors and Op Area Around Detected Ignition to Support Rapid Response.
  - Red Flag Warning operations.
  - Rapid emergency corridor establishment in the event of an ignition detection; “flashing lights and sirens in the air,” taking priority over other traffic.

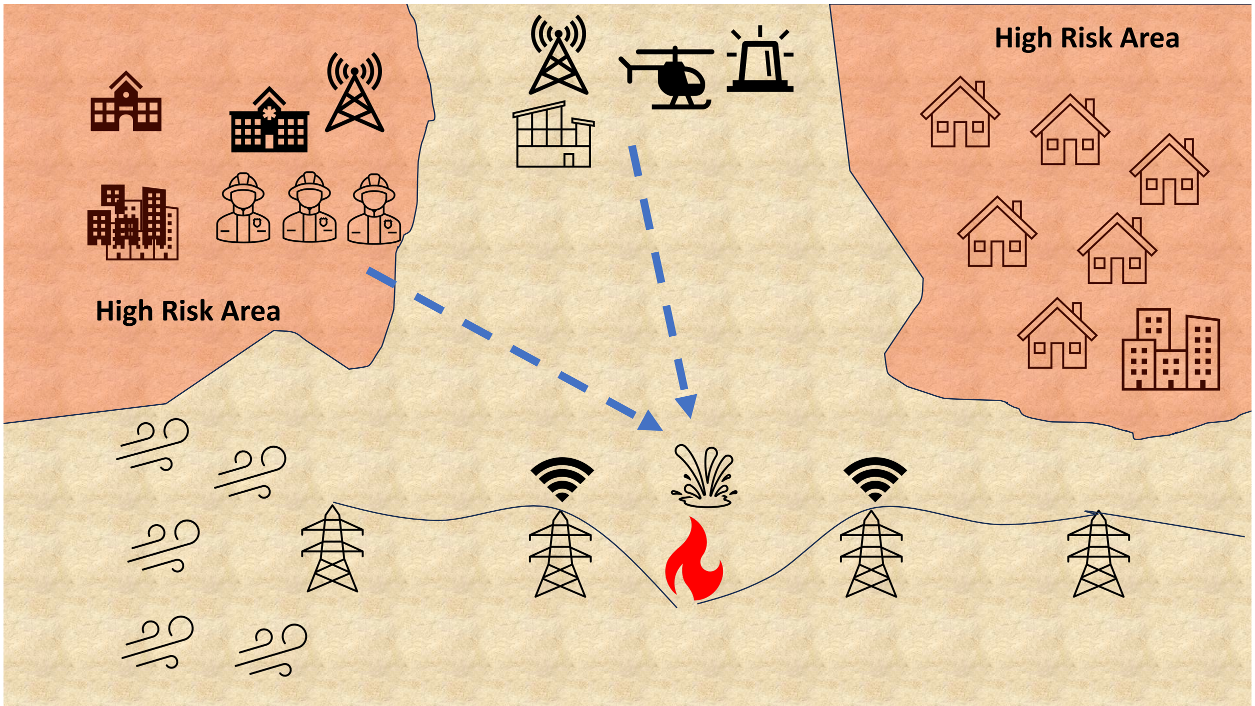
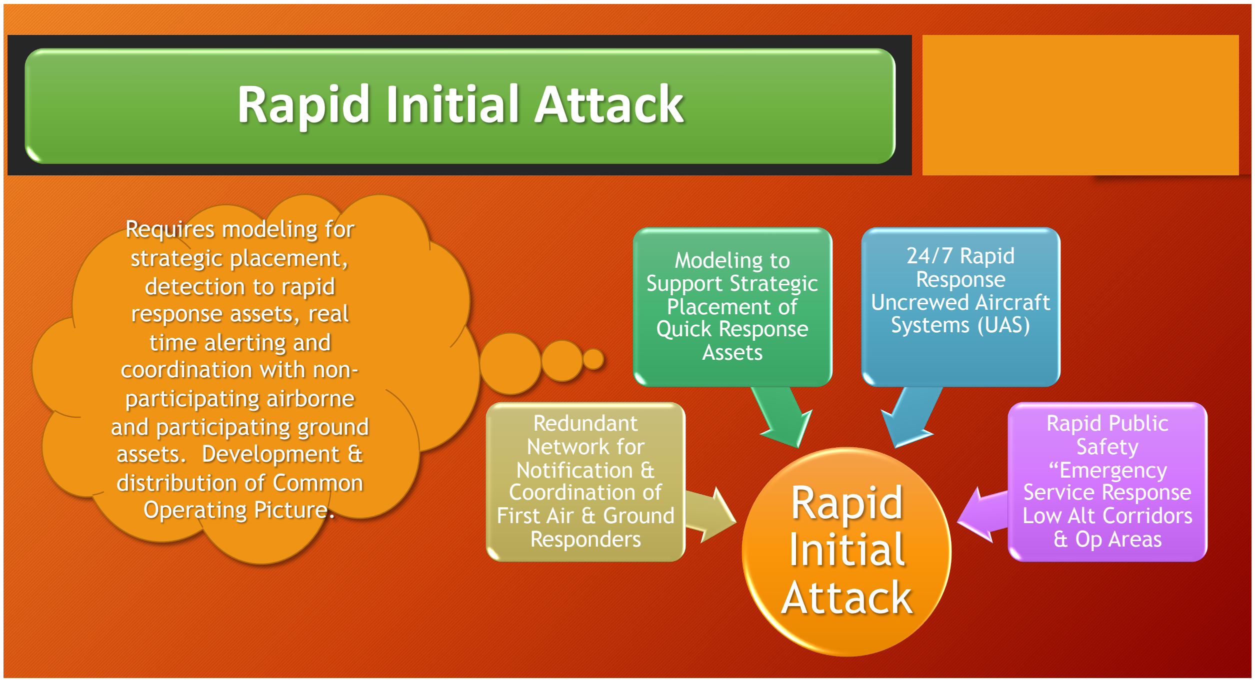


Figure 24. Illustration of Strategically Placed Automated Rapid Response Initial Attack UAS Alerted by Utility Fault Indicator Responding in Concert with Ground Forces to Suppress Ignition.

Key supporting technologies for the desired future state of rapid initial attack include high fidelity data collection, analytics, and modeling to determine the optimum location of these quick response assets, persistent, redundant, and automated notification and coordination networks, development of electronic ID and locating standards and requirements for all aircraft operating in this airspace, and a robust, role-based common operating picture that ensures the right information/decision support products are delivered to the right people in relevant time.



Rapid Initial Attack

Requires modeling for strategic placement, detection to rapid response assets, real time alerting and coordination with non-participating airborne and participating ground assets. Development & distribution of Common Operating Picture.

Modeling to Support Strategic Placement of Quick Response Assets

24/7 Rapid Response Uncrewed Aircraft Systems (UAS)

Redundant Network for Notification & Coordination of First Air & Ground Responders

Rapid Public Safety “Emergency Service Response Low Alt Corridors & Op Areas

Rapid Initial Attack

Figure 25. Rapid Initial Attack Requirements

5.9.3 Extended Attack/Support

Whether in the initial attack stage or in those instances where a wildfire grows to necessitate extended attack (EA), we must remember that it is highly trained firefighters on the ground who extinguish and confirm the fire is out. Since 1930, aviation has provided these brave men and women with critical direct and indirect suppressant and retardant support, overwatch, resupply, personnel movement, and emergency extraction services [287]. While best used in direct coordination with ground firefighters in the field, aviation can also serve an important role in slowing the fire’s growth and advance before ground firefighters arrive or during periods when it is unsafe for them to be on the fire line. However, there are significant aspects of that air support that have not progressed since that first suppression drop from an aircraft, 93-years ago. As then, aerial firefighting today remains a largely clear air, daytime enterprise. While darkness is a well-understood limitation of current aerial firefighting aircraft (outside a small handful of special night programs), many are unaware of the daily impact that smoke from an evolved wildfire can have. While the intense heat of an active wildfire can cause the smoke to rise to great heights, leaving clear air below in which firefighting aircraft can safely operate, over time, as the fire extends, adiabatic and night time cooling often results in the smoke settling close to the ground from the early morning hours until the heat of the day causes it to rise again [288]. In some cases, this phenomenon can ground traditional crewed firefighting aircraft for multiple consecutive days. On average, aerial firefighting aircraft don’t launch until between 10AM and 12PM, leaving wildland fire incident commanders and firefighters in the field with only access to this critical support for approximately 1/3rd of each available 24-hour period. This significant limitation was first identified and extensively researched and written about by the U.S. Department of the Interior’s (DOI) Office of Aviation Services (OAS) beginning in 2014 [289]. It was also identified as a top challenge to be solved by participants in the 2021 NASA ARMD Wildfire Management Workshop of May 13, 2021: “Increase the suppression duration in day and night (24/7) through automated aircraft, automated airspace operations, and safety assurance methods to ensure persistent and safe operations.” The following sections will detail the desired future state of extended attack and other critical aviation support functions in support of ground firefighters and the communities they protect.

5.9.3.1 24/7 Extended Attack in All Degraded Visual Environments (DVE's)

In developing the ConOps for providing 24/7 extended attack in DVE's, the desired future state considered a range of technological, organizational, cultural, operational and safety factors. First, let's discuss the value proposition of having a 24/7 all-DVE extended attack capability. As has been related above, for the last 93-years extended attack support for firefighters has largely been a clear-air, visual flight rules (VFR) endeavor that limits that support to approximately 1/3rd of every 24-hour operational period. This means that during the remaining 2/3rd of the operational period (~16-hours), the wildfire can continue to grow, uncontested by aerial suppression or retardant support. However, the impact of this gap goes beyond the many hours when this support is not currently provided. Often during the night and daytime DVE periods, the winds diminish, the temperatures are lower than during the clear-air periods, and the relative humidity (Rh) is higher. Each of these weather factors make the wildfire more vulnerable to the effects of suppressant and retardant applications, making this 16-hour gap in support even more significant. Being able to support 24/7 all-DVE extended attack not only means being able to increase that available support window by 200%, but it also enables that support during some of the fire's most vulnerable periods (Figure 26). While aerial suppressant and retardant is always more effective in coordination with ground firefighting operations, it is also clear that expanding extended attack operations into extended DVE periods when the fire can be more vulnerable to its effects can also result in firefighters facing a potentially small fire with less intense fire behavior than under currently constrained extended attack support periods.

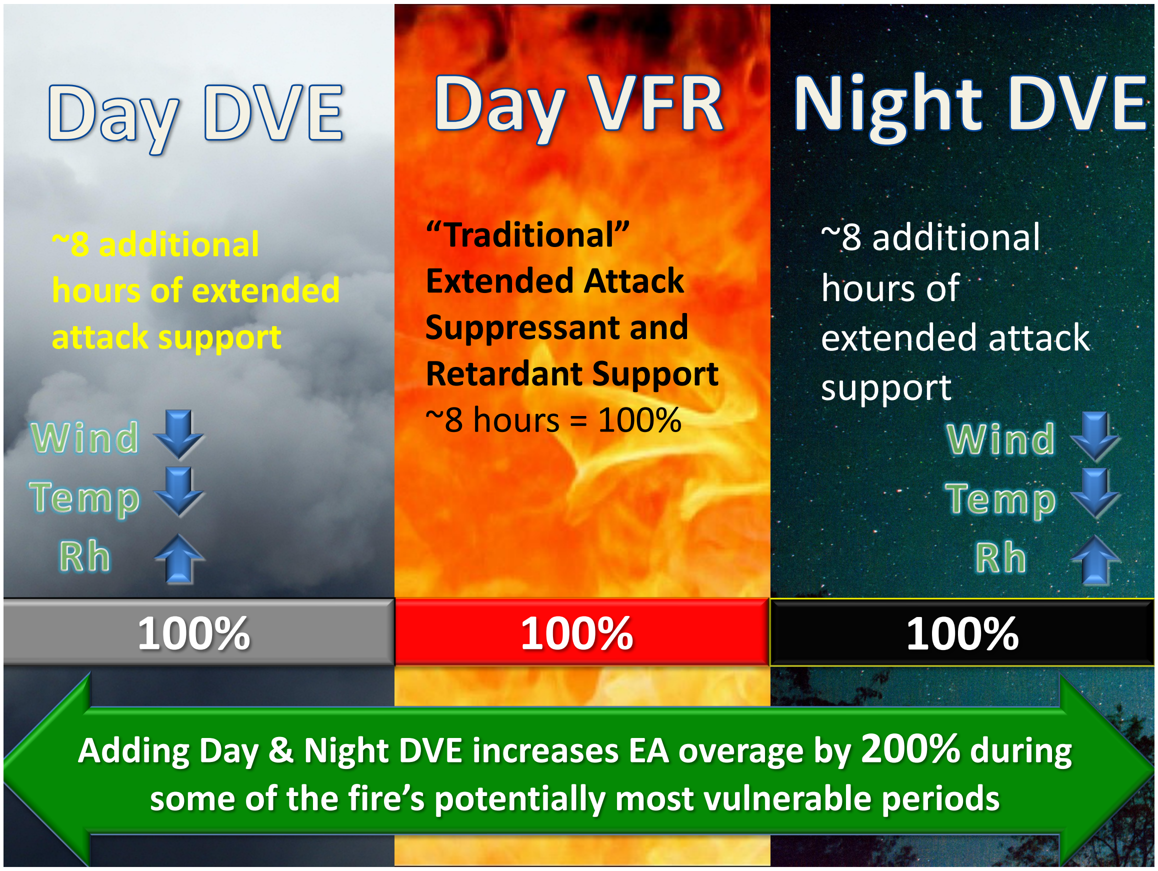


Figure 26. The Value Proposition for 24/7 All-DVE Extended Attack (EA) Support Coverage.

So, what is the potential outcome value of a 200% increase in the available EA coverage and that coverage occurring during some of the fire's most vulnerable weather periods? While that is a question for further study and analysis, we can project the potential value based on current suppression and acres burned data. According to the National Interagency Fire Center (NIFC), in 2022 wildfires burned 7,577,183 acres and resulted in the expenditure of $3.5B in suppression funds (does not include Preparedness or Recovery funding). From this, we could project that if the 200% increase in suppressant and retardant delivery coverage during these DVE periods resulted in just a 5% improvement in wildfire containment performance, that could, based on 2022 figures, result in 378,859 fewer acres burned and potentially $175M in reduced suppression expenditures. Given estimated cost to complete the KMAX optionally piloted helicopter integration into the wildland fire mission following the 2014 and 2015 demonstration flights was only $10M, even a smaller than 5% performance improvement from this 200% increase in EA coverage would represent a significant return on investment (ROI) [290].

Having established the value propositions for expanded EA operations, what operational factors should be considered in selecting the right method for bridging these current gaps? Factors considered in developing the desired future state ConOps include:

Flying in night and day DVE periods is hazardous.

Lack of traditional visibility, coupled with uneven and often severe terrain, and the presence of natural (e.g., tree snags) or manmade (e.g., towers, wires, etc.) obstacles represent significant safety challenges. While technology to support outfitting traditional crewed aircraft with sensors and synthetic vision devices that would enable them to fly in both DVE periods could be developed, that technology has already been developed and proven on large UAS derived from FAA certificated aircraft, eliminating the risk to pilots [291].

Fixed Wing vs. Rotary Wing?

Suppressant and retardant carrying aircraft come in both forms, but are their considerations that favor one over the other in filling these DVE gaps? While helicopters can often be temporarily based close to the fire, often within the temporary flight restrictions (TFR) that are established over large, evolved wildfires, fixed wing tankers and scoopers launch from traditional airfields and often commercial airports. This presents unique challenges when considering the possible use of uncrewed fixed wing aircraft to bridge the two current DVE gaps. First, their transit from the airfields to the fire and back requires extensive coordination with the FAA. Second, and perhaps more problematic is the likely public resistance to full-scale "robot" airplanes operating from the airports embedded in their communities and from which they and their families fly commercially from. Given the challenges of these factors, the desired future state envisions remotely operated helicopters, based within the TFR (enabling easy beyond visual line of sight – BVLOS operations) as the logical first entrant into this space.

Safety of other aircraft and ground personnel is always a consideration when integrating UAS into an operation.

In the case of applying a remotely operated aircraft derived from an FAA certificated helicopter, there are several safety advantages. First, as an aircraft originally designed to carry humans, these aircraft are equipped with redundant critical systems and other safety measures that built from scratch UAS are not equipped with. Likewise, as an aircraft already certificated to fly in the national airspace system (NAS), these aircraft will be equipped with all the requisite ID avionics, making them electronically visible to air traffic control and other similarly equipped aircraft. Finally, their size makes them more easily seen than other, small UAS.

Logistics and support for aircraft working on a wildfire is always a consideration.

Within the operating area of the fire and the TFR, basing and support space is at a premium. As a result, the future state envisions the remotely operated helicopters used to bridge the DVE gaps will be configured as optionally piloted helicopters. This approach has many operational, organizational, and cultural advantages. First, it eliminates the need to double the number of helicopters required, reducing both basing issues and cost. It also enables continued traditional crewed operations during the clear-air day periods. This should reduce any pilot resistance to the incorporation of this expanded capability (they continue flying as before). It also supports the higher cycle rate of drops that hand-flown crewed helicopters are capable over the remotely piloted configuration that will largely be flown using preprogrammed waypoints. And for those companies flying these dual-purpose aircraft, they can expect additional flight time and revenue through the expanded operations, while only incurring the incremental cost of retrofitting their helicopters with the optionally piloted package (i.e., control integration, communications, sensors, etc.). By simply including the remotely piloted capability as a line item on existing contracts, the government can also achieve efficiencies. The optionally piloted configuration also makes it easy to reposition the aircraft to the next fire, ferrying it in the piloted mode to the next fire via normal NAS protocols.

After considering these factors, the desired future state envisions the use of helicopters equipped to fly on fires with onboard pilots during traditional clear-air periods and then in the remotely piloted configuration during the day and night DVE periods. Currently evolving large UAS (>55 lbs.) and advanced air mobility (AAM) electric vertical take-off and landing (e-VTOL) are also envisioned to play an important role in this and other related use cases described below [292]. Use of AAM in fighting wildfires can help illustrate the early value of these aircraft to the public and could advance their acceptance of their broader future application in other public safety use cases and in the daily movement of people and goods [293].

5.9.3.2 Suppressant/Retardant Drop Outcome Effectiveness Measures

Suppressant and retardant drop outcome effectiveness measures have continued to challenge wildland firefighting agencies. In a 2009 report, the USDA Office of the Inspector General (OIG) concluded the agency had failed to use accepted aviation firefighting performance measures to demonstrate cost-impact for its current and proposed future firefighting aircraft [294]. A subsequent 2013 Government Accountability Office (GAO) report reiterated a long-standing concern from the 1960's that neither USFS and DOI had devised and instituted credible methods to collect information on the outcome performance of their suppressant and retardant dropping aircraft. [295]. In response to these and similar concerns from Congress, the USFS conducted a 9-year, $11M Aerial Firefighting Use and Effectiveness (AFUE) study [296]. While the report provided some insight into the general effectiveness of selected aerial firefighting aircraft, it failed to deliver protocols and methods that could easily be applied to measuring suppressant and retardant drop outcome effectiveness in future fires and with respect to other aircraft [297]. During DOI's 2014 and 2015 demonstration flights of the KMAX optionally-piloted helicopter in wildland fire representative missions, it was found that the onboard infrared sensor that was used to assist the aircraft in navigation, water drop targeting, and terrain/obstacle avoidance was able to detect the wetted area from its previous drops (1:48 – 2:27 on the July 12, 2019 DOI video compilation of the 2014 and 2015 optionally piloted helicopter demonstration flights at the New York State FAA UAS Test Site and at Lucky Peak Reservoir, Boise, ID at this link: **https://www.youtube.com/watch?v=End3FzSNpms**). Through this data, the wetted area could be measured and through AI/ML algorithms that measured any color differential within the wetted area, a measure of the post-drop burn through could be determined (white cold, black hot in this case), providing further drop outcome measures. Additionally, the image could aid the remote operator in real time to adjust his subsequent drop based on the observed outcomes. Accordingly, the desired future state envisions equipping all suppressant/retardant dropping aircraft with similar sensors to collect these kinds of outcome effectiveness measurement data for real-time use and to support subsequent postflight and Post-Fire analytics.

5.9.3.3 Supply/Maneuver Support to Ground Firefighters

While the DVE impact on aerial suppression and retardant aircraft operations is clear, it also impacts the ability for aircraft to provide ground firefighters with the resupply and maneuver support that enables them to fight the fire safely and effectively. Firefighters in the field are in constant need of resupply (e.g., water, food, replacement equipment, parts, etc.). As the fire conditions and perimeter change, they need to be ready to quickly move themselves and their equipment. Often located far from suitable roads, firefighters often rely on helicopters for this critical support. As with extended attack crewed helicopters, the helicopters that provide this support to firefighters on the ground are similarly restricted from operating during the regular day and night DVE periods. Especially when the thick smoke of large, evolved fires can ground traditional aircraft for days, this gap in support can prevent ground firefighters from combatting the fire and put them at risk. In 2014 and 2015, during DOI's optionally piloted helicopter wildland fire demonstration flights, the KMAX demonstrated the ability to deliver four designated cargo loads to predetermined GPS-designated locations on a single flight, using a four-point carousel rig [298]. The demonstration also included flight over a designated route that kept it clear of overlying simulated firefighter positions and incorporated an inflight update to one of the drop locations, which it performed without error. Similarly, in the 2014 demonstration flight, the KMAX delivered a 6-wheeled Gator vehicle in a 12-person rated cage suspended from the aircraft on a long line, simulating the movement of equipment and personnel to a new location. In the future state, regular day, and night DVE's will not prevent ground firefighters from receiving needed supplies or maneuver support. Remotely operated helicopters, able to safely fly in DVE's, providing this critical support when and where required.

5.9.3.4 Emergency Firefighter Extraction

Firefighting is a hazardous vocation. In 2022, there were 25 wildland firefighter fatalities during operations. In addition, seven firefighters were injured in chainsaw accidents, 12 in vehicle mishaps, 17 hit by falling trees, and 12 injured through entrapment by fire [299]**.** Many of these accidents resulted in significant injuries that required immediate medical attention. While firefighters are trained in first aid, often these injuries require care that is unavailable in the field. Often fighting the fire far from easy road access, aviation has always provided a quick method of emergency extraction. Emergency extraction is such a high priority with ground firefighters that bureau managers have previously requested that specific line items be written in DOI fire helicopter contracts to allow emergency extraction via empty water-carrying buckets (aka Bambi buckets) when no other alternative exists. As with the two previous uses cases, the emergency extraction of firefighters by helicopters severely constrained by DVE's. The same technology that could open the ~16-hours of daily DVE's to suppression/retardant and firefighter resupply/maneuver support could also be used in the emergency extraction role to save firefighter lives.

5.9.3.5 Persistent Precision Mapping and Surveillance

Accurate and timely mapping of wildfires is critical to effective wildland fire management and firefighter safety. A 2007 study revealed that manually mapped wildfire perimeters were subject to significant errors, particularly in areas of increased terrain complexity [300]. Many agencies, including NASA's Science Mission Directorate (SMD), and Space Technology Mission Directorate (STMD) have made significant contributions to wildfire mapping, data fusion, and related technologies. Likewise, industry and academia have also invested significant time, effort, and resources into this issue. While advances in remote sensing, UAS, satellites, HALE, MALE, and traditional aircraft, geographic information system (GIS) data processing, and AI have been made, a ConOps to vet, test, integrate and adopt an integrated solution into daily wildfire perimeter mapping practices has not been achieved. Achieving this begins with accurately defining the breadth of requirements for precision mapping and surveillance in wildland fire management. As we have outlined in our discussion of previous links in the wildland fire chain, effective surveillance data collection requires a complementary and integrated system of platforms, sensors, and data analytics capabilities. Wildfire perimeter mapping requires precision sensor and positioning technologies on a platform with the endurance, range, and connectivity necessary to map large, dynamic multi-front wildfires in relevant time. Some current long-endurance (18-24hr) sUAS have been used in this capacity, but require the use of multiple, overlapping aircraft (and spares in the event of an inflight malfunction or unavailable aircraft) to ensure persistent 24/7 coverage. Future HALE and MALE aircraft will provide longer persistence but are largely still in development and testing. Another future opportunity is to equip current crewed aircraft (e.g., tankers, helicopters, aerial supervision module aircraft, lead planes) with mapping and surveillance sensors, automatically incorporating them into the network while they are in the fire traffic area (FTA). While not possible just a few years ago, the continuing development of smaller, lighter, less power hungry, and higher precision sensors for drones have now made this an option that could be done without significant modification or burden to the aircraft. Data from commercial and government satellites have become more readily accessible, precise, and through their greater numbers, less constrained by the orbital limitations of having to rely on a single satellite.

While persistent precision mapping and surveillance tools are important to wildland fire incident commanders (IC) and division supervisors, Hot Shot crews, Smoke Jumpers, and other tactical firefighting crews benefit from unit level tactical precision surveillance tools, most often in the form of sUAS that can easily be carried into the field, robust and easy to operate under arduous conditions.

The future state of persistent precision mapping and surveillance foresees an integrated, overlapping system of space-based, traditional crewed aircraft, small and large UAS within the FTA, HALE, and MALE aircraft above the FTA, all contributing through a persistent connectivity network (expanded discussion on that below) that supports far-edge collection and analytics, networking to near-edge mobile data centers, and to the cloud for expanded processing, analytics, and modeling. AI, which has increasingly been incorporated by agencies and industry to improve the precision, forecasting, and utility to firefighters and the public will also play a large role in the future state of persistent precision mapping and surveillance [301], [302].

5.9.3.6 Tactical Overwatch and Command and Control (C2)

Tactical overwatch are critical functions in effectively managing wildland fires and supporting firefighters on the ground. Traditionally the function of air tactical group supervisors (ATGS) or aerial supervision modules (ASM), it is currently a labor intensive, visually oriented process typically conducted from aircraft like the Beach King Air and requiring the monitoring of a half dozen or more radios at one time. As a result, their focus is primarily on safely and effectively managing the air assets with limited direct interaction with ground supervisors. The desired future state seeks to build on work conducted by DOI in 2018 that investigated incorporating sUAS into these important functions. During the August 2018 Taylor Creek Fire in Oregon, a contracted ScanEagle sUAS was overhead at 8,500' providing overwatch surveillance support for fire crews engaged in night burn out operations along a containment line on the west side of the fire, defined by a road where the firefighters were operating from. Using its onboard infrared (IR) sensor, the UAS patrolled the containment line, looking for spot fires started by blowing embers. Observing several spot fires, the UAS operator reported this information via radio to the firefighters working the fire. With authorization from the division supervisor, the UAS operator contacted a BLM fire engine and reported the location of the spot fires behind the containment line. The UAS operator was then able to precisely direct the engine down the road toward the fires, where holding crew of firefighters disembarked and were directed through the dense brush and difficult terrain toward the spot fire by the UAS operator. Able to see the firefighters through the onboard IR sensor, the UAS operator successfully directed the firefighters to the spot fire, which the crew reported as approximately 1ft by 1ft and nearly impossible to see with the naked eye. Through this close collaboration and coordination between the overwatch UAS and firefighters on the ground, a potentially deadly spot fire behind the containment line was quickly located and extinguished before it could grow [303].The future state foresees expanded use of UAS in direct tactical overwatch and command and control support for ground firefighting operations. Another UAS-based overwatch and C2 application in direct support of extended attack aircraft was uncovered during 2015 DOI UAS testing over a managed wildfire at the Olympic National Park. Flying overhead in a designated altitude block, the IR sensor on the ScanEagle followed a water bucket equipped helicopter as it approached the fire front to make a drop. What the UAS operated noticed was that the helicopter did not drop in the optimum location relative to the fire's edge. Upon further discussion, it was determined that because the pilot was relying on visual clues from the flame, he had a less precise picture of the fire front than the UAS operator equipped with an IR sensor (00:15 – 00:47 on the video at this link: https://youtu.be/VdVaL4eHJts). This observation opened the possibility to use tactical overwatch UAS to assist extended attack suppression aircraft in delivering their loads more precisely for improved results [304]. In summary, the future state envisions the use of long endurance UAS over the fire serving in direct tactical overwatch support roles for both ground firefighters and aircraft, providing each with enhanced situational awareness and performance.

5.9.3.7 Cooperative Airspace Management for Crewed and Uncrewed Operations

To understand the complexities and challenges of aerial wildland firefighting coordination and control one need only consult the NWCG Standards for Aerial Supervision [305].

> Aerial firefighting occurs in a very dynamic environment. Firefighting aircraft often work in close proximity to each other, ground personnel, and surrounding terrain. This is routinely accomplished under conditions that are less than ideal as aircrews contend with high temperatures, wind, turbulence, and visibility restrictions caused by smoke and terrain. Furthermore, firefighting aircraft, in contrast to most commercial aviation, must provide their safe separation. It is for these reasons that airspace coordination is of the utmost importance to safety. Though the aerial supervisor is responsible for overall control of aircraft on an incident, it is incumbent upon all aircrew personnel to participate in this endeavor by adhering to the rules set by policy and the instructions given by the aerial supervisor.

With an average of 70,000 wildfires per year (1983-2022), occurring across disparate areas across the country and often in remote locations, wildland fire managers have been forced to develop airspace management procedures and protocols that can be implemented where traditional airspace management coverage may not exist, is spotty, or is unable to scale to accommodate the urgency and/or load of additional aircraft that must be brought in to fight the fire. To accomplish this ability to coordinate and control aircraft anywhere and under any conditions, current wildland fire airspace management is founded on using geographic, altitude, and temporal separation, establishing visually significant holding and initial points (IP's), and ingress and egress routes for aircraft sequencing and separation. Airspace coordination and aircraft separation is also heavily reliant on establishing and maintaining clear radio communications among all participants. This is all coordinated through the Air Tactical Group Supervisor (ATGS) who can normally be found overhead the fire, usually in a King Air style aircraft, monitoring a half-dozen radios or more.

Despite the significant documentation and regular reviews of wildland fire airspace management procedures, the required training for all participants, and the regular confirmation of pilot competency by government pilot inspectors, the wildland fire airspace has repeatedly proven to be among the most hazardous airspace environments in government aviation operations. A review of the DOI Aviation Safety Summary and Annual Reports from 2008 through 2022 bears this out, documenting numerous "near-miss" encounters between firefighting aircraft, accidents involving fatal controlled flight into terrain, and fatal mid-air collisions of aircraft both during day, clear-air firefighting operations [306]. Aircraft mishap rates in the wildland fire mission have historically exceeded mishap rates in all other DOI mission areas, including those with similar hazard and risk profiles (e.g., search and rescue, low level wildlife surveys, extended overwater support missions, etc.). A 2015 Centers for Disease Control and Prevention study of aviation-related wildland firefighter fatalities in the U.S. between 2000 and 2013 found that across the wildland fire community, 78 deaths occurred in 41 separate mishaps involving 42 firefighting aircraft, with 45% of those resulting from midair collisions, failure to maintain terrain, water, or obstacle clearance, or pilot loss of control [307]. These adverse trends in wildfire aviation safety continue today. On August 7, 2023, two

CalFire firefighting helicopters collided in mid-air during daytime operations in Riverside County, CA., resulting in three fatalities [308]. Improving safety of current crewed aircraft operations is the number one priority of the desired future state of collaborative wildland fire airspace management.

Since UAS were first tested and evaluated during wildfire operations in 2015, they have increasingly become a valued support tool for ground firefighters, division supervisors, and incident commanders [309], [310]. They have proven their worth in being able to see through thick smoke with onboard IR sensors to detect unforeseen hotspots and then being able to direct firefighters to them. They have improved the safety of aerial ignition on prescribed burns and have opened a new capability to conduct night burn out operations in support of managing active wildfires. In DOI's FY2020 Annual UAS Summary and Annual Report, it was revealed that from 2017-2020, 20% of DOI's 30,300 UAS flights were in direct support of interagency fire missions [311]. As with traditional crewed wildland firefighting aircraft, UAS are separated from other aircraft by geographic, altitude, or temporal boundaries. While this manual process has worked to date, it severely limits the number of UAS that can be flown on a particular fire and complicates any potential beneficial coordination between UAS and crewed aircraft. Improving the safe and effective integration of UAS and crewed firefighting aircraft over wildfires is another priority of the desired future state of airspace management.

Wildfires by their nature are dynamic events where fire managers must often react quickly to changing conditions. The ability to deliver the right mix and scale of resources in a timely manner can often make the difference between the wildfire being one of the 98% of wildfires contained in the first 24-hour operational period or one of those 2% that account for 97% of the acres burned and suppression costs. This is particularly true in instances when firefighters are using aircraft to build extended defensive lines of retardant or delivery large amounts of suppressant to protect significant values at risk. If a retardant line cannot be completed in time, fire can run through the resulting gap, rendering all that effort useless. An example of this occurred during the Beaver Creek Fire near Sun Valley Idaho that ran from August 7th to August 31st, 2013, and burned 114,900 acres [312]. On August 13th, a long retardant line was being laid on a ridgeline that represented the last barrier between the wildfire to the north and homes and infrastructure to the south [313]. Due to limitations on the number of tanker aircraft that could be effectively managed within the traditional airspace management protocols, the line was not completed before the cessation of flight operations that day, leaving a sizable gap for the fire to escape through toward the homes and infrastructure below. Fortunately, the winds changed that night, preventing the fire from reaching the retardant line until it could be completed the next day. This instance illustrates the need for improvements in wildland fire airspace coordination and management that will support scaling the number of aerial firefighting resources to meet dynamic ground support requirements. Figure 27 illustrates the combined objectives of the desired future state of wildland fire airspace management.

Figure 27. System Objectives for the Future State of Wildland Fire Airspace Management.

Meeting the three system objectives for the future state of wildland fire airspace management requires the following capabilities:

Robust Far-Edge Electronic Position and Vector Awareness Technology

Traditional crewed aerial firefighting aircraft are a mix of contracted (federal, state, local, tribal, territorial, foreign), government-owned (federal, state, local, tribal, territorial. While all these aircraft are equipped with Automatic Dependent Surveillance-Broadcast (ADS-B) Out systems, their UAS counterparts, flown under Part 107 are prohibited by the FAA from using ADS-B Out. While UAS are now required to be equipped with remote ID systems (RID), the FAA's chosen broadcast (vice network) approach renders the RID capability ineffective for providing precise UAS positioning information to other aircraft. The desired future state solution includes an onboard vehicle-to-vehicle-to-infrastructure (V2V2I) system that enables each participating wildfire aircraft to report its precise position and vector to adjacent aircraft (and to the cooperative airspace management system described in a later section). Among the benefits of this far-edge information sharing capability is that as a decentralized system, it can provide critical real-time coordination and collision avoidance system (C&CAS) support, while also supporting the information requirements of the near-edge cooperative wildland fire airspace management system). This could serve to mitigate the risk of midair collisions that continue to plague crewed firefighting aircraft. Further, it could also provide terrain proximity and collision warnings that could mitigate the risk of CFIT, another leading cause of crewed firefighting aircraft mishaps and fatalities. There is also precedent for mandating this kind of unique identification and reporting technology within the federal aerial firefighting community. Conceived and developed by the USFS, the automated flight following (AFF) system is an online government application that automatically tracks the location and velocity of specially equipped aircraft and mobile assets and provides this information in near-real-time to dispatchers, aviation managers, and other authorized users [314]. It has been a required installed equipment item for all wildland firefighting aircraft for years. Similarly, V2V2I equipment could be mandated for all wildland firefighting aircraft. In the desired future state, development of the C&CAS capability supported by the V2V2I communications system would include providing recommended course and/or altitude changes to operators of two aircraft approaching an advisory level proximity gate and within certain collision warning parameters, automatically initiating those actions to mitigate a collision. Such technology exists today in many automobiles that at first warn the driver of the proximity of other cars or the side of the road and then if the situation approaches extremis, takes action to avoid the collision.

Mobile, Near-Edge Collaborative Wildfire Traffic Management System

The V2V2I technology described above provides critical awareness and real-time coordination and collision avoidance to improve safety. However, fully achieving the other objectives of the future state of wildland fire airspace management requires a mobile, near-edge collaborative wildfire traffic management system (WTM). Operating at the near edge of the fire, adjacent to the far-edge V2V2I systems, WTM would benefit from fewer communications, latency, data storage, and networking challenges than if solely based in the cloud. Similar in concept to NASA's UAS Traffic Management (UTM) system and the FAA's UTM ConOps (V2.0), WTM would support more complex wildfire operations in denser airspace, including enhanced support for BVLOS operations in clear air and DVE's. In conjunction with the aircraft installed V2V2I systems, WTM would safely and effectively support the dynamic demands and expectations for a broad spectrum of wildland fire missions, from suppression/retardant drops, surveillance, mapping, weather monitoring, firefighter resupply and movement, emergency extraction, and others.

5.9.3.8 Remote Sensing

Remote sensing is one of those capabilities that provides support across all three phases of the wildland fire lifecycle and the seven-underlying links in that system chain. In an evolved wildfire, effective remote sensing is particularly critical to the safety and efficiency of the full range of extended attack activities due to the dynamic nature of this link. The first step in understanding the remote sensing needs in this or any other link in the wildland fire system chain is to determine the strategic and tactical objectives of remote sensing across the range of supporting extended attack activities. With the high-level objectives identified, specific remote sensing data product requirements can be developed (Figure 28). This will support the selection and prioritization of preferred remote sensing systems, methods, product processing, and dissemination. Today, remote sensing is identified with satellite, airborne, and terrestrial sensors that gather data from across the electromagnetic spectrum and/or the physical world (e.g., weather, vegetation, and soil moisture levels, etc.). Many are passive, while others employ active measures to sense their surroundings (e.g., radar, LiDAR, etc.). These systems are subject to the limitations of the sensor, the platform on which it is mounted, and the processing system to which it is connected. Data standards, quality, latency, security, and reluctance to sharing across organizations are among the current identified gaps in remote sensing (note: data products, display, and dissemination, and connectivity are discussed below, separately). Another current gap in the current state of remote sensing is the lack of attention to humans and the machines they operate as valuable remote sensors. This represents incredible lost opportunity in the extended attack element of the wildfire chain when potentially thousands of firefighters and scores of vehicles could be involved in fighting the fire. Some of these shortcomings are currently being addressed through the USFS's Dingell Act Resource Tracking pilot projects [315].

In the desired future state, data standards will be developed and adhered to, federated learning will be incorporated to break down the barriers to data sharing among disparate partners, and far-edge and near-edge compute technologies will be employed to mitigate the networking demands of ever-growing data ingest, while providing faster, richer data products to operators in the field. Additionally, ongoing advancements spurred on by the UAS industry to reduce the cost, and size, weight, and power (SWaP) requirements while also enhancing the resolution of remote sensors will be leveraged to distribute and network them more widely to other assets within the wildland fire ecosystem (e.g., traditional crewed aircraft, ground vehicles, firefighter personal protective equipment, etc.).

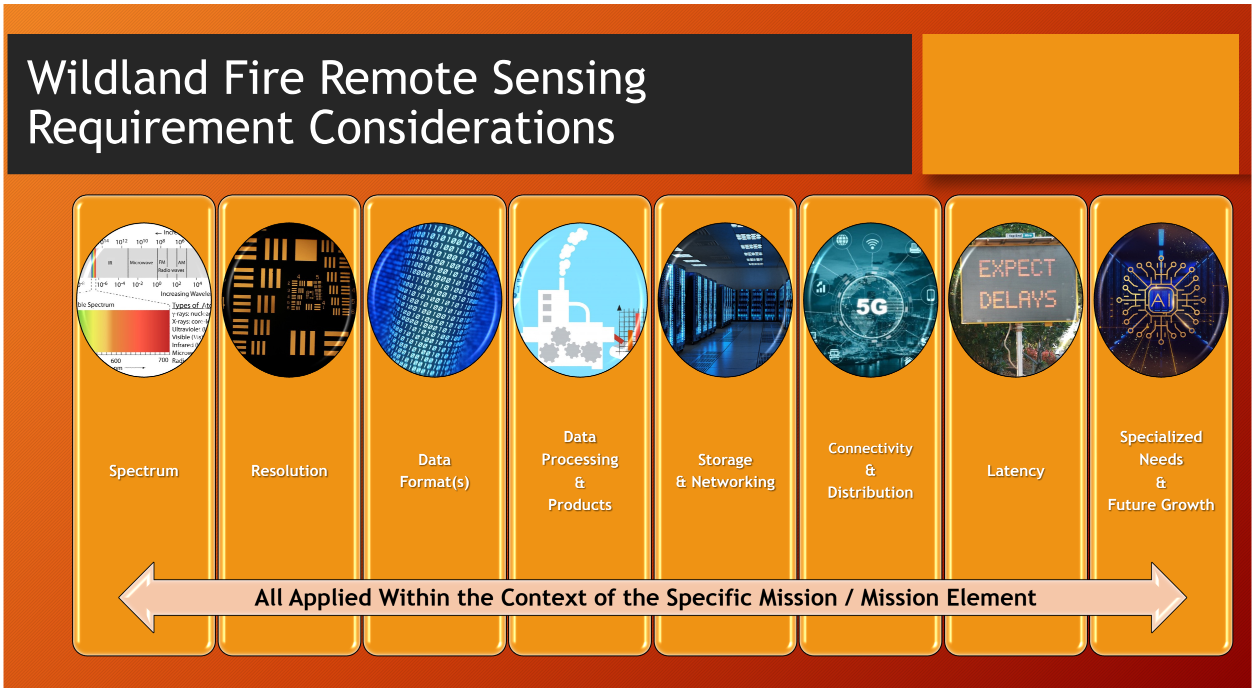


Figure 28. Sample Wildland Fire Remote Sensing Requirement Considerations.

5.9.3.9 Common Operating Picture

Today, wildland fire incident commanders, division supervisors, ATGS, and other key personnel lack a timely, accurate, and relevant common operating picture (COP). This pervasive lack of situational awareness can have significant wildfire management performance and safety implications. There are many factors that have contributed to the current state. We have previously discussed the challenges of defining data collection objectives, requirements, and standards above. In the following section we will discuss the challenge of persistent connectivity, which is paramount to realizing the full potential of a future state COP. Other challenges to delivering a COP in the future state are more organizational and cultural than technical.

Wildland fire is managed through an amalgamation of interagency partners that include all levels of government, private contractors, and even prison inmates. In addition to the permanent wildland firefighters in each agency, many seasonal firefighters are brought on every fire year. The cost and logistics of equipping such a large and diverse workforce with specialized equipment to support the distribution and display of a COP is beyond the means of the agencies that support wildland fire, which has been a past barrier to addressing the COP gap.

Wildland fire managers have also expressed concerns about the perceived field support and potential workforce distraction (and related safety) issues with providing widespread access to a COP. Wildland firefighters are already burdened with significant personal protective and mission-essential equipment. They often operate deep in the field, away from traditional infrastructure and technical support services. Also, as the NWCG Preparedness Guide for Wildland Firefighters and Their Families points out, *"It is usually against crew rules to use cell phones on the fireline or during work hours except in the case of emergencies since safety of the wildland firefighter and those nearby depends on focus and professionalism* [316]. *"*

Additionally, wildland fire managers have expressed concerns when any new technology introduction is proposed. As one firefighter put it, *"when you're standing in front of a 50-foot wall of flames, you don't want to have to rely on a piece of technology that hasn't been thoroughly tested and trained to* [317]. *"* The wildland fire community has throughout its history experienced the proposal of many "good ideas" that fell short in first seeking to understand the mission and its many complex challenges and including them in every step of the system development, testing, training, and field integration processes.

These are all legitimate concerns. The desired future state addresses these both for the development of a COP and other proposed technologies through a similar collaborative approach to requirements development, testing and validation that proved successful in the development of DOI's "Drone for Good" program [318].

Specific to the COP, the desired future state foresees a collaborative approach that has the following attributes.

- Takes advantage of the ubiquitous nature of personal smartphones to address agency cost and logistics concerns of having to buy dedicated equipment to support COP. As firefighters routinely carry their personal smartphones with them, as with similar government "bring your own device" (BYOD) programs offers the potential to eliminate the cost and logistics challenges of providing a COP on government-issued equipment.
- Leverages current smart phone application and zero-trust (ZT) cyber security methodologies to provide a secure and role-based approach to providing the right data products to the right people in a role-meaningful depictions in relevant time. Potential COP users would download a designated app and would log on to their specific fire, using their role-based credentials that would define their access level. COP users would only see what they needed to see based on their specific roles and responsibilities.
- Builds on approach of many commercial smartphone apps to enable user location data to be shared via the COP app. This could also serve to address requirements of the 2019 John D. Dingell Act and support current interagency Dingell Act Resource Tracking (DART) research [319].
- Provides the capability for "emergency alert" functionality (like Amber, Severe Weather, etc. alerts) to notify firefighters of impending danger, including immediate actions to take to preserve their safety. This could potentially prevent entrapments, burn overs, and save numerous firefighters' lives.
- Enables limited, targeted inputs to the COP from firefighters. Highly experienced firefighters in the field, trained in critical areas like wildfire behavior, fire weather, etc. can be a rich source of timely and valuable observations of dynamically changing conditions. The future state COP concept of operations would incorporate role-based functionality to enable firefighters to provide quickly and easily relevant, "Waze-style" value-added inputs into the COP [320]. Through a similar graphical icon-based approach, firefighters could easily select and share critical information (weather/fire behavior changes, embers flying over the containment line, firefighter injured by chainsaw, tree, vehicle, etc.) quickly and with minimal distraction.
- Supports the incorporation of augmented reality (AR) features. Similar recent smartphone supported gaming and mapping applications, role-based AR access could valuable information overlays to smartphones and tablets. As an example, it could provide field supervisors with critical situational awareness to the location of nearby ground and air units, values at risk, and critical infrastructure. It could also assist in directing personnel to lost or injured firefighters or guiding them on evacuation routes, particularly in dense smoke environments.

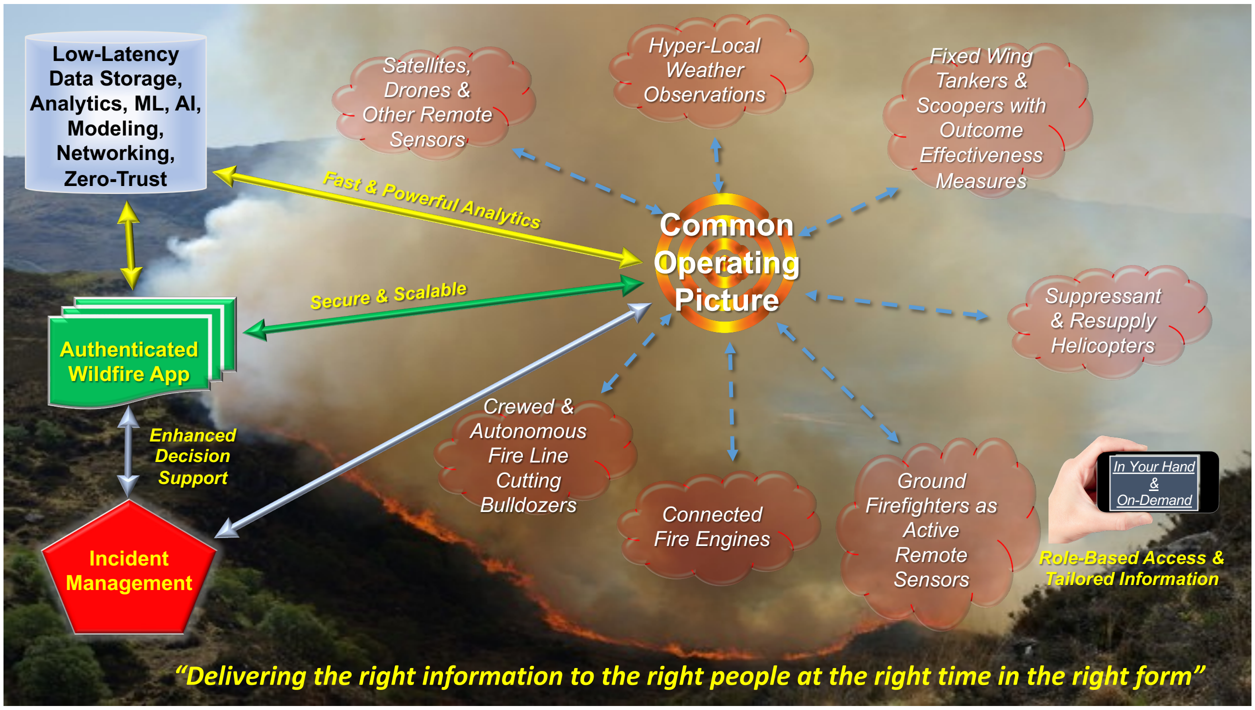


Figure 29. Desired Future State Common Operating Picture.

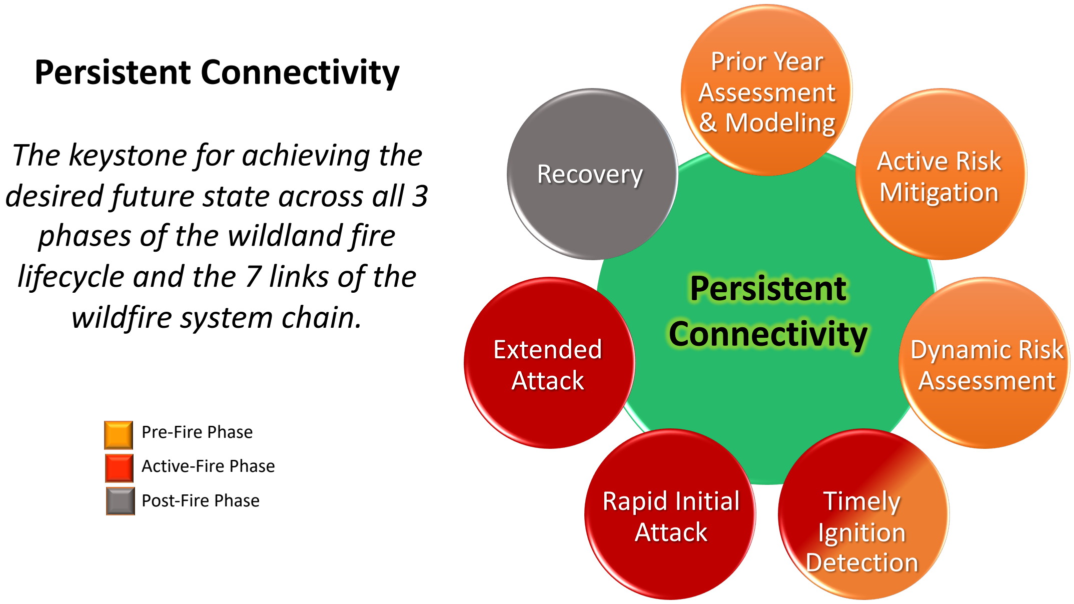
5.9.3.10 Persistent Connectivity

Throughout the discussion and description of the desired future state across the 3 wildland fire lifecycle phases and 7 links in the wildland fire system chain, connectivity has played a central role (Figure 30). This requirement has also been a consistent theme in interagency wildland fire workshops including the NASA ARMD Wildfire Management Workshop of May 13, 2021 [321] and the NASA System-Wide Safety Wildland Firefighting Operations Workshop of March 9-11, 2022. [322]. Without persistent connectivity, the desired future state of wildland fire cannot be realized. To achieve the desired future state, persistent connectivity solutions must address the following key considerations:

- Wildfires can occur without notice, anywhere in the U.S. Wildland fire persistent connectivity solutions must be highly mobile and region agnostic, able to work across all 50 states and U.S, Territories.
- Wildfires often strike in remote areas where traditional wireless connectivity is absent or adversely affected by terrain.
- Even when wildfires ignite in areas where robust wireless connectivity exists, these networks can be overwhelmed by the large number of personnel and resources brought into fight the fire and resultant fire damage to the existing wireless and electrical infrastructure.
- Persistent connectivity solutions must be able to work without interfering with existing communications infrastructure. Unlike military or private industry use cases that may support the establishment of private connectivity networks, wildland fire persistent connectivity solutions must strive to work in harmony with existing U.S. connectivity providers.
- Future state persistent connectivity solutions must retain high scalability. Data growth worldwide continues to expand exponentially, with projections of a greater than 50% increase in just the next two years [323]. As improved remote sensing, data analytics, AI/ML and digital twin modeling, airspace management, and other technology-focused solutions are developed and integrated into the future state of wildland fire, the demand for these services and the data necessary to support them will similarly grow.

Solutions must fit within the wildland fire agencies' ability to fund, deploy, and train to these new systems.

The desired future state of persistent connectivity will successfully address these considerations through a layered and redundant system of systems that will leverage a combination of low-earth orbit satellites, HALE/MALE/UAS aircraft communication nodes, 5G/6G connectivity, software-defined networks, Wi-Fi 6, low-power networks, mesh networks, advanced spectrum management, optical fiber, and related technologies.



Persistent Connectivity

The keystone for achieving the desired future state across all 3 phases of the wildland fire lifecycle and the 7 links of the wildfire system chain.

🟧 Pre-Fire Phase
🟥 Active-Fire Phase
⬛ Post-Fire Phase

Persistent Connectivity

Prior Year Assessment & Modeling

Active Risk Mitigation

Dynamic Risk Assessment

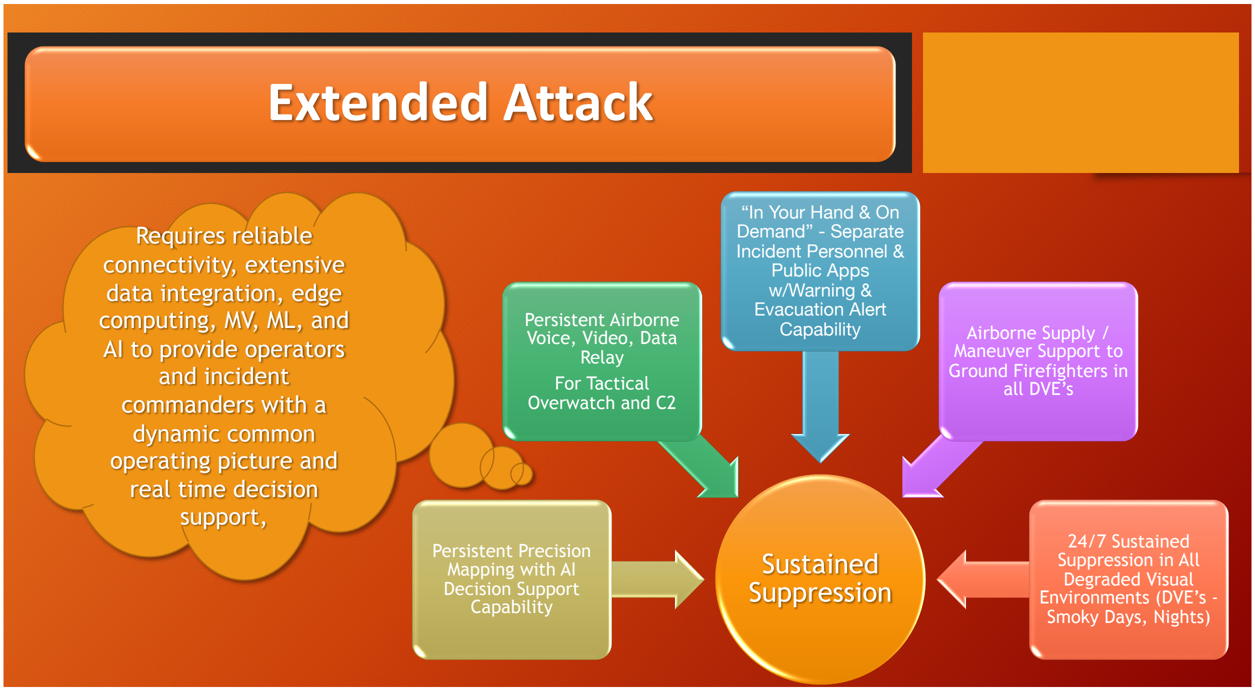
Timely Ignition Detection

Rapid Initial Attack

Extended Attack

Recovery

Figure 30. The Overarching Importance of Persistent Connectivity to Realizing the Desired Future State.



Extended Attack

Requires reliable connectivity, extensive data integration, edge computing, MV, ML, and AI to provide operators and incident commanders with a dynamic common operating picture and real time decision support,

Persistent Airborne Voice, Video, Data Relay For Tactical Overwatch and C2

"In Your Hand & On Demand" - Separate Incident Personnel & Public Apps w/Warning & Evacuation Alert Capability

Airborne Supply / Maneuver Support to Ground Firefighters in all DVE's

Persistent Precision Mapping with AI Decision Support Capability

Sustained Suppression

24/7 Sustained Suppression in All Degraded Visual Environments (DVE's - Smoky Days, Nights)

Figure 31. Expanding Extended Attack Support to Ground Firefighters and the Aircraft that Assist Them.

5.10 Post-Fire

5.10.1 Recovery

The recovery link in the wildland fire system represents an important transition point from the Active Fire to the Post-Fire phase (Figure 32). Often beginning before the fire is contained and the incident management team is demobilized, Post-Fire actions are initiated to repair suppression activity damages and minimize the potential erosion and run-off fire-generated hazardous substances [324]. Rapid assessments of affected watersheds, conducted as part of emergency stabilization by burned area emergency response (BAER) teams are also conducted to identify immediate actions necessary to prevent further damage from subsequent storms, winds, etc. In the future state, these activities will benefit from advances in remote sensing, data analytics, AI/ML enabled modeling, and decision support tools developed and deployed to support the Post-Fire management. Leveraging the same federated learning principles that supported the sharing of data from disparate actors, the immediate recovery efforts will also benefit from continued access to dynamic local weather observations and predictions and critical inputs and observational data from crowd-sourced local home, land, and business owners.

As efforts later transition to the long-term and burned area rehabilitation stages, these same technology tools will speed the time and fidelity of assessing critical treatment projects to preserve future landscape and community resiliency. As the long-term restoration process progresses over multiple years, advanced data collection, analytics, and predictive modeling technologies developed to support the preceding phases and links will provide recovery and restoration managers and affected communities with timely program status insights and data-supported recommendations for actions to mitigate future wildfire risks.

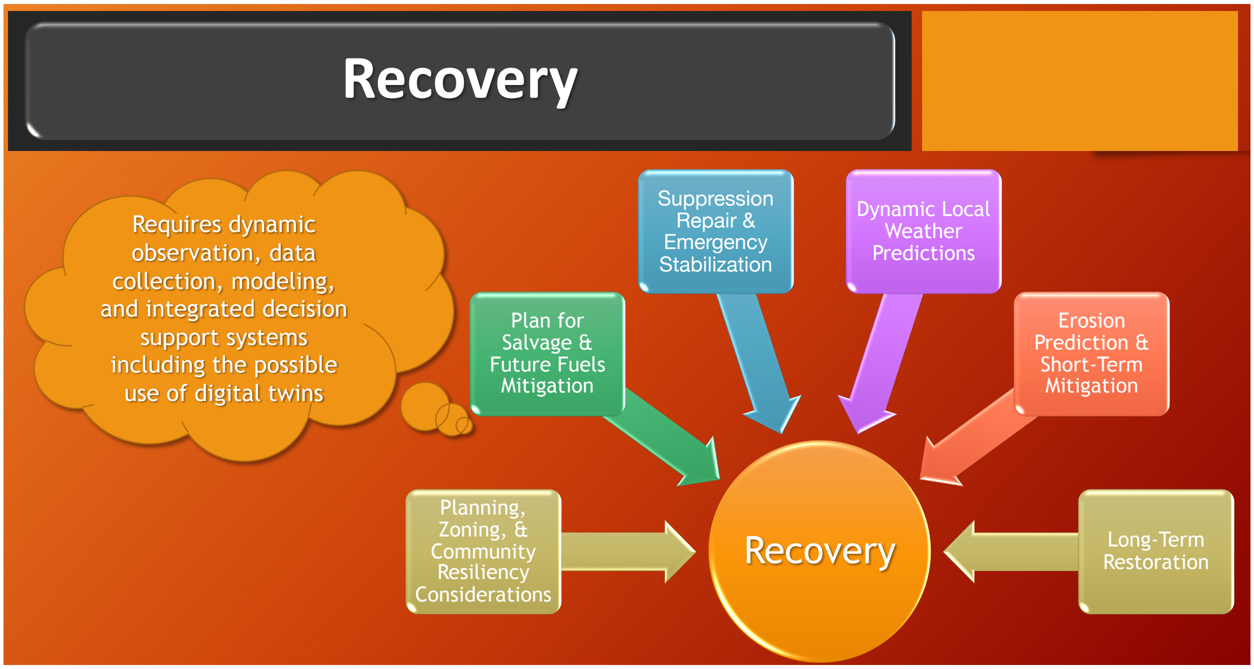


Figure 32. Post-Fire Phase, Recovery Link, Representative Activities, & Future State Enablers.

5.11 Wildland Fire Organization

For the technology goals outlined in desire future state to be achieved, the future state must be matched with an organizational and cultural alignment that supports these goals while also maintaining its current wildland fire operational and safety responsibilities. In *Section 4 Current State of Wildland Fire in the U.S*, we illustrated the diverse and complex web of federal, state, local, tribal government, industry, academia, trade association, and oversight stakeholders that govern and influence wildland fire policy, standards, and operations in the U.S. These and other wildland fire organizational and management challenges have been outlined across a variety of official government reports, including, but not limited to:

- Government Accountability Office (GAO) Audits [325].

- Agency Office of the Inspector General (OIG) Reports [326], [327].
- Congressional Wildland Fire Mitigation and Management Commission Report [328].
- Congressional Budget Office (CBO) [329].
- Blue Ribbon Panel Report to the Chief, USDA Forest Service and Director, DOI Bureau of Land Management [330].
- NASA Wildfire Research Reports, Workshops, and Presentations [331], [332], [333], [334], [335].
- President's Council of Advisors on Science and Technology (PCAST) Report to the President – Modernizing Wildland Firefighting to Protect Our Firefighters [336].

Across these reports, four organizational challenge themes predominate: Focus, Structure, Funding and Culture.

5.11.1 Focus

For many decades, the focus of wildland fire management organizations has been on quickly suppressing all wildfires. This long-term predominant focus on extinguishing fires has prevented the other key connecting links in this system of systems from receiving the funds and support necessary to realize their full potential, resulting in an imbalance that degrades overall performance. While high-level strategic wildland fire policy documents (e.g., National Cohesive Strategy), recent legislation and agency initiatives (e.g., USFS, DOI plans for increased fuels treatment) have brought renewed focus (and funding) to the prevention of wildland fires and mitigation of their damage through broad proactive measures, legacy suppression-focused agency organizational and budgetary alignments remain fully entrenched. Achieving the desired future state requires a wildland fire organizational construct that can deliver the balanced focus across the full wildland fire management system of systems.

5.11.2 Structure

The current wildland fire organizational structure is heavily aligned toward operations. Given the decades of focus on the preparation for and conduct of wildfire suppression, this comes as no surprise. The charter of National Wildfire Coordinating Group (NWCG), the preeminent interagency wildland fire governance group outlines its responsibilities "to develop, maintain, and communicate interagency standards, guidelines, qualifications, training, and other capabilities that enable interoperable operations among federal and non-federal entities." Notably, it mentions nothing about identifying, developing, testing, and integrating new supporting technologies [337]. Not surprisingly, the 99 committees under NWCG's purview are similarly focused on preparing for and conducting wildland fire operations [338]. The inbuilt challenges this structure presents to bringing new technologies to the wildland fire mission were captured by the PCAST in their recent report to the President:

> "The needs of our wildland firefighters overlap substantially with those of America's warfighters. Whereas we have a national commitment ensuring that our warfighters are not sent into harm's way without the best of American science and technology at their disposal, no similar organizational framework exists to protect and empower wildland firefighters."

The PCAST report further remarked that critical aspects of wildfire response are *"stuck-technologically and organizationally—in the last century."* While the operations-focused structure of interagency wildfire management organizations is a large contributor to this, the PCAST report pointed to the absence of a unified executive wildfire management body with authority to direct actions across agencies. It noted that the National Interagency Fire Center (NIFC) is a location where the primary federal fire agencies convene with state partners to coordinate firefighting efforts, not an empowered interagency wildland fire management authority. While there is significant collaboration among the federal wildland fire agencies (e.g., USDA-Forest Service, DOI, NOAA, FEMA-USFA, NSF, NASA, DOD) and their state (National Association of State Foresters) and Tribal (Intertribal Timber Council) partners, agencies are free to develop their own approaches to wildland fire research and development (R&D) and technology integration.

A good illustration of this consequence is the distributed wildfire R&D landscape across these agencies:

1. USDA Forest Service conducts R&D at nearly 80 locations across the U.S., organized around five research stations, and two research centers, complemented by a network of 80 experimental forests.
2. The DOI Office of Wildland Fire (OWF) leads the interagency Wildland Fire Information and Technology (WFIT) program which manages existing systems and develops new ones across a wide range of wildland fire related applications. The OWF Information Technology website currently lists 12 "in use" WFIT applications while a search of the full WFIT investment inventory includes168 applications [339], [340].

3. Also, within DOI, the U.S. Geological Survey (USGS) has a robust fire science program that conducts R&D across a wide range of fire science disciplines [341].
4. The National Oceanic and Atmospheric Administration (NOAA) is currently conducting 11 separate wildfire research efforts [342].
5. Under the Department of Homeland Security (DHS) and Federal Emergency Management Administration, the U.S. Fire Administration is actively engaged in research on wildland fire sensors (in conjunction with DHS Science and Technology), the use of augmented reality, the effects of structural separation, and applications to support a common operating picture [343].
6. The National Science Foundation (NSF) has a Wildfire Interdisciplinary Research Center (WIRC) whose mission is to conduct high-impact wildfire research to provide new predictive tools and informed strategies [344].
7. NASA has a long history of research, development, and testing of wildland fire technologies [345], [346], [347].
8. On the state side, CalFire's Office of Wildfire Technology Research and Development focuses on evaluating new and novel approaches to fighting wildfires. Its current initiatives include AI, last mile connectivity, and internet of things (IoT) [348], [349].

The State of Colorado Center of Excellence for Advanced Technology Aerial Firefighting focuses on technological advancements to improve aerial firefighting practices [350]

Although many of these individual agency R&D efforts collaborate with fellow agencies, the fragmented structure and lack of an empowered executive interagency authority to direct, coordinate, and manage these initiatives is significant impediment to achieving the technology-supported safety and mission performance goals of the desired future state.

Even with the implementation of an empowered executive interagency authority to direct, coordinate, and manage wildland fire technology exploration, development, testing, evaluation, and integration, current agency wildland fire organizational structures lack the necessary technical supporting positions. Agencies like DOD, DHS, and NASA have offices and staff specifically aligned to support technology identification, development, and integration. Many of these positions also require specific test and evaluation or program management training and certifications [351]. Conversely, many wildland fire technology-oriented positions require a wildland firefighter certification, with no similar requirement for test and evaluation or program management. To achieve the desired future state, wildland fire agencies should either add specific technology development and integration offices and positions with requisite training and certification requirements or partner with NASA and similar agencies to leverage their resident expertise and experience in these areas.

Another adverse consequence of the current number of federal, state, local, tribal, and territorial wildfire organizations and authorities is in having and implementing consistent standards. This has been a consistent theme among the interviews with interagency wildland fire managers and industry partners that informed the whitepapers, the tabletop exercises, and the working group meetings that have informed the development of this ConOps. This sentiment was also widely expressed by participants of March 2022 NASA System-Wide Safety Wildland Firefighting Operations Workshop:

> "Participants added the interpersonal conflict between firefighting groups and their associated jurisdictions as a major challenge in observing routine operations. Disparate firefighting groups, government entities, and local stakeholders all have unique sets of wildland firefighting policies, priorities, and operational procedures that rarely align with one another. When technology changes hands (such as when the Forest Service seeks to adopt systems developed by the Department of Defense) or when an active fire crosses jurisdictional boundaries (such as out of the wildland and onto a vineyard), communication, coordination, and transfer of responsibility present a significant challenge. Participants indicated that improving general communications infrastructure and data sharing capabilities, including standardizing operational procedures between groups, are open research problems [352]."

Although the NWCG has collaboratively developed extensive equipment, position qualification, and procedural standards across wildland fire, ensuring compliance and consistent application of these standards continues to be problematic. Wildland fire aviation is a good example for this. Although federal and state representatives developed and agreed to interagency fire helicopter standards, in 2015 the State of Montana was prohibited from operating their highly modified excess military helicopters on federal fires because they did not meet those standards, restrictions that continued for years [353]. Similarly, today California and Colorado are buying firefighting helicopters that are not fully certificated by the FAA and do not possess Supplemental Type Certificates (STC's) for their firefighting modifications, potentially placing them in similar jeopardy of not being permitted to fly on federal wildfires by USFS and DOI. [354], [355]. This lack of unified standards and application has also adversely affected the continued adoption of UAS. Since 2019, the cybersecurity requirements and standards have varied among the federal, state, and local firefighting agencies. This has resulted in confusion among industry partners, a reduction in innovation, and some government organizations being banned from using their drones on Federal fires [356]. Again, the lack of a unified and empowered executive interagency authority to direct wildland firefighting standards and procedures nationwide is an impediment to achieving the desired future state.

5.11.3 Funding

There is a common misperception that because combatting wildfires is such a "front-page" national issue that costs billions of dollars annually, wildland fire agencies must also be as well-funded to develop and field new supporting technologies. The reality is much different. For fiscal year 2023, the combined federal discretionary appropriations requested for DOI and USDA (the primary Federal Departments responsible for wildland fire) was only 6% of the DOD requested total [357], [358], [359]. While the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA) provide $24B in funding for wildfire issues, it is distributed across 40 different programs, administered by a dozen agencies, and like the DOI and USDA wildland fire appropriations, focused predominately on active prevention and suppression of wildfires, with little devoted to technology identification, development, testing, and integration [360]. As a result, funding to support new wildfire technology development and integration must come from the agencies' prevention and suppression budgets. Those decisions are made by the same agency managers and executives responsible for wildland fire preparation and suppression outcomes, making it difficult for them to approve requested technology development funding. A good example of how this funding and organizational structure works against new technology implementation is the 2014 and 2015 KMAX optionally piloted helicopter (OPH) testing in support of future all-DVE initial and extended attack operations. Following two-years of industry funded technology development and testing and leveraging $123M in previous DOD RDT&E, the remaining technology integration costs to field this capability were estimated at $10M [361], [362]. While wildland fire managers understood and agreed with the likely future benefits of this technology, they were forced to make the difficult decision between applying this $10M to current wildland fire suppression equipment requirements or investing in future technology. As a result, the all-DVE KMAX OPH capability was never fielded, leaving aerial firefighting coverage of the initial and extended attack/support missions at traditional 6-8 hours per day.

It's also been suggested that wildfire technology development funding could leverage emerging private sector initiatives toward the same goal. The industry-funded development and testing of the KMAX OPH in 2014 and 2015 and more recent industry funded wildfire technology investments offer promise, but as mentioned above, without the government's commitment and ability to complete the field integration, industry will be less inclined to invest in future efforts. Another potential source of wildland fire technology development funding is the current XPRIZE competition to innovate wildland firefighting technologies [363]. However, as with industry-funded efforts to jump start technology innovation and development, government wildland fire agency funding must be there to carry these initiatives through to field integration and adoption.

The PCAST report to the President reinforces these findings:

> "…pilot projects funded by the federal government have demonstrated technologies to give wildfire incident commanders constant, real-time, situational awareness of all firefighters on the scene of an active fire. But in many cases, the fire services are left to implement this technology translation by themselves on an ad hoc basis in the snippets of time not consumed by fighting fires, refurbishing equipment, training, or clearing fuels to reduce fire hazard. Their efforts are further constrained by budget structures, which specify what work they must be doing when using various funding lines, such as fire suppression or hazard reduction [364]."

To achieve the desired future state, wildland fire management funding must be sufficient and appropriately aligned to meet the emphasis that has been placed on the development and integration of new technology to ensure that wildland firefighters do not face tomorrow's fires with yesterday's tools.

5.11.4 Culture

It is well-established that organizational culture can influence the success or failure of change management initiatives, including technology adoption. This is even more true in the wildland firefighting culture, where poorly implemented technology innovations can result in loss of life. Wildland fire agency participants in the March 2021 NASA System-Wide Safety Wildland Firefighting Operations Workshop of March 2021 identified an additional cultural barrier to technology adoption, "the mental cost involved in training to unlearn old habits and adopt new technology [365]." Understanding and working within the current wildland fire culture is foundational to the successful development and integration of new technologies that underpin the desired future state. This starts through close interagency engagement and wildland fire workshops (like those NASA has held over the past few years), where agencies can freely share ideas and concerns and learn from each other. When those conversations transition to discussions and potential actions on technology discovery, development, and implementation, a well-defined, fully collaborative approach can serve to break down cultural barriers and lead to success (Figure 33).

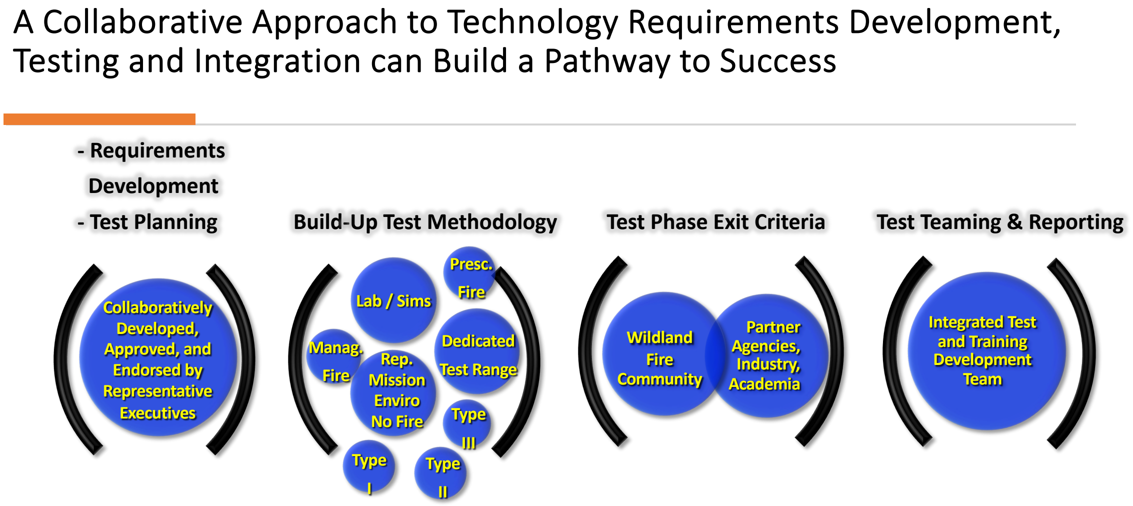


Figure 33. A Collaborative Approach to Technology Development, Testing, and Integration Success.

5.12 Conclusions

As reinforced in the February 2023 PCAST report to the President, critical elements of wildland fire management are *"stuck-technologically and organizationally—in the last century."* The desired future state offers opportunities to bring wildland firefighting into this [41] and establish updated and enduring processes, protocols, and funding, and organizational structures that will continue to support sustained modernization to ensure the safety of our firefighters and the communities they protect. Achieving the desired future state requires a boldly different approach than the one that has resulted in the current state if we are to meet the significant challenges of this growing national threat.

5.13 Recommendations

Achieving the desired future state of wildland fire management requires a multi-faceted, integrated approach that should include the following recommended elements:

1. Treat wildland fire as an integrated and interdependent system of systems, establishing a balance among the components that optimizes the overall performance of the full system.
2. Refocus, restructure, and fund wildland fire management in a manner that restores system balance across the three phases and seven integrated elements of wildland fire and promotes seamless cross-jurisdictional and cross-agency interoperability across all federal, state, local, tribal, and territorial stakeholders.
3. Understand, respect, and collaborate with the wildland fire culture to achieve needed and desired safety and performance improvements.

6 Notional System Architecture(s) and Operational Scenarios

- Architecture TBD: info/figures in work

6.1 Information Exchanges and Desired Capabilities

TBD

6.2 System Requirements

TBD

6.3 Performance Requirements or Considerations

TBD

7 Summary of Impacts

The following is a summary of operational and organizational impacts of the proposed system on the users, the developers, and the support and maintenance organizations. It also describes the temporary impacts to these parties during the period when the new system is being developed, installed, or trained on. This initial inclusion is intended to allow all affected organizations to prepare for the changes that will be brought about by the new system and to allow for planning of the impacts on the buyer agency or agencies, user groups, and the support maintenance organizations during the development of, and transition to the new system.

Note: The *Summary of Impacts* will perhaps be the section that changes the most between version 1.0 (this document) and version 2.0 of the ConOps, as it will rely heavily on stakeholder feedback to best capture the scope and realism of implementation. In the interim, *Section 9 Analysis of Proposed System* serves to tabulate the changes envisioned in the Future State.

7.1 Data, Communications, and Connectivity Changes

7.1.1 Creation of a Universal Data Platform

The Common Operating Picture, which supports the increasingly complex operations recommended in this ConOps, will require a universal, device-agnostic, data platform that can be accessed by varying roles and in varying operational scenarios. Present-day data and communication pipelines lack the bandwidth, persistence, and robustness necessary to support envisioned future operations. Many of the changes in this regard will be infrastructure-related to accommodate the large increase in scope for the use of higher fidelity and more frequent methods of data sharing and communication, without an increase in latency. Use of edge-computing, signal boosting, and creation of consistent networks between various nodes within the wildland firefighting arena will require new radio frequency blocks and new satellite links to transmit large amounts of data in real time, with the associated hardware for transportation and visual display. Compounding these changes is the increased need for information security across the digital domain, especially as government agencies are the end-user of many of these envisioned tools.

7.1.2 Creation of a Common Data Repository

To support this ConOps' goals of resource-sharing across jurisdictions and ensuring assets do not go unused when in need because they are not discoverable, the creation of a common repository of resources is necessary. Such a repository will have to incorporate a standard registration format across entities and should ideally include data gathered concerning the efficacy of a given resource with regards to past fire scenarios. The common resource repository and universal data platform will both require significant investment in development and training, as well as continued support for maintenance, updating, and hosting. Universal standards for data types will be necessary to enable the source-agnostic common data platform described in the previous section. A regulatory body will have to begin the process of defining universal standards for data types to ease the incorporation of novel sensors and other data sources into this larger remote sensing network.

7.1.3 Incorporation of AI/ML and Other Novel Data Processing Techniques

In order to increase throughput of the current data processing bottleneck and enable the in-time data requirements put forth by this ConOps, significant research and development into AI, ML, and improved data processing techniques will be needed. In addition to a significant increase in total data and memory size for analyses, a key aspect of AI/ML in the future state is to uncover trends and patterns within wildland fire that are not obvious with humanity's current understanding. AI/ML in the Future State will also seek to model wildland fire more precisely and accurately across any environment, including weather, landscapes, and WUI's in real time.

7.1.4 Procedures for Active Fire Assessment and Operation Effectiveness

New methods of assessing the effectiveness of active-fire suppression efforts in real time will require standardization and incorporation into the operation procedures. For example, to assess the effectiveness of a retardant drop from a tanker aircraft, the observation and measurements of the drop and surrounding fire will need to be defined and performed, either by a person on site or by a piece of equipment operated remotely. In the spirit of reproducibility, this will require a procedure that can be followed by different people on different days for different fires.

7.1.5 Information Security

The topic of information security of course pops up many times in the discussion of data and communications in the future state, and further discussion on this topic is contained in Section 9. With the idea of interoperability, interagency data sharing, and overall increase in scope, so too must the security of this infrastructure equitably keep pace. Perhaps most importantly is the fact that many of the end users of data and communication software in the wildland firefighting sphere are federal agencies, which are subject to a constant barrage of cyber-attacks and other nefarious acts relating to geopolitics.

7.1.6 Retention

Moving into the mid-late 21st century and preparing for the 22nd century, it is the duty of contemporary research and analyses to retain the data and work conducted for future use. This serves multiple purposes: First, raw data stored can be preserved for future analyses that may use technology and techniques that have yet to be invented, opening the door to new revelations. Likewise, the wildland environment will certainly look much different 50-100 years from now, especially with the impacts of climate change and population growth, and retained data can assist in revealing trends and sets of control for future technology verification and validation. In the short term, this is critical from the standpoint of assessing the effectiveness of this ConOps as it gets implemented incrementally. Infrastructure and processes will need to be defined for retention up to an appropriate amount of time for relevancy.

7.2 UAS and the National Airspace

7.2.1 Procedures for Expansion of UAS Operations

At present, UAS are used in a limited capacity for wildland firefighting. The large-scale adoption of UAS for use in prescribed burns, remote sensing, and operational use envisioned by the ConOps will require the creation and adoption of novel procedures to enable a safe transition to this new future state. Such procedures will naturally dovetail with a modification of existing aircraft and the adoption of new aircraft, corresponding to flight performance and maintenance criteria. Likewise, the intended expansion of aerial operations to visually degraded and nighttime conditions in both duration and scope of simultaneous aerial operations will require extensive modification to current airspace management procedures. This is especially true as uncrewed aircraft become more heavily relied upon.

7.2.2 Procedures for Modification of NAS Regulations

For aerial firefighting — whether crewed or uncrewed — quick, safe, and legal access to the NAS is of upmost importance. This means quick and efficient establishment of an area of operation or TFR, with persistent enforcement to non-participating aircraft. Current processes for TFR creation and modification of its geometry in real time will need to be improved to adapt to the dynamic fires we are seeing in the present day. This includes low altitude transit corridors connecting aircraft bases to the area of operation during ingress and egress with minimal flight restrictions that might impede response. Additionally, new processes and procedures for integrating the operation of UAS legally in the NAS with minimal advanced notice will be essential to the success of future robust responses.

7.2.3 Universal Standards

At present the adoption of universal standards is stymied by standards and requirements not keeping pace with the development of novel UAS and other technologies. This ConOps requires rapid adoption of novel airspace users, and the development of standards and requirements development for their operations will have to be fast-tracked for their timely adoption in wildland firefighting.

7.3 Vehicles, Equipment, and Hardware

7.3.1 Procurement of Novel Assets

To support the diverse operations, significant data gathering, and complex future operations put forth in this ConOps novel vehicles, equipment, and hardware will need to be procured. Such new assets will be varied and may fall outside of traditional procurement pipelines.

7.3.2 Modification of Existing Assets

Modification of existing assets will be required to expand operations into visually degraded and nighttime operations as this ConOps recommends. Existing assets will need to be equipped with the sensors necessary for DAA and other safety features to ensure safe operations when new users are in the shared airspace. Furthermore, existing air and ground vehicles, as well as current sensing platforms, should be equipped with additional sensors to feed into the larger data network for remote sensing and data gathering.

7.3.3 Procedures for New Tools, Equipment, and Technology

Inevitably, as new equipment and technology folds into operations as envisioned in the future state, any existing procedure will require adjustment to either incorporate the appropriate link to a new procedure or explicitly define a new procedure. In this sense, all documentation associated with the current wildland firefighting methodologies will be subject to updates. For a majority of cases, changes shall be transparent and occur naturally in the current review and update cycle, which is typically an annual occurrence. Organizations are encouraged to follow proper protocols for enacting temporary allowance in the interim, such that approvals do not impede the implementation of new tools. For example, this includes formal “red-line” edits, or other methods for periods of short-term approval. A few specific areas of focus for new procedures called out in the Future State are discussed below; however, this is not exhaustive.

7.3.4 Quality Assurance

In the future state described in this ConOps, interoperability of assets across different regions is essential to dynamically manage severe fires. The creation of a baseline set of standards to qualify an asset for operation regardless of jurisdiction and holding equipment and vehicles which have a high value to such interoperability will be essential to prevent assets that could otherwise be useful from being grounded simply because of a mismatch in qualification standards.

7.4 Roles

7.4.1 Positions and Responsibilities

With new equipment, technology, and procedures in place, the Future State will come with additional duties to be filled by existing or new personnel. For example, uncrewed aircraft will require either a remote pilot or other type of main operator for deployment and retrieval---a job that would look very different from existing pilots in a cockpit. Further, this position may be augmented with additional tasking, such as being a liaison between the firefighters and air traffic controllers (of the FAA). With information security, there will likely need to be more security officers and IT personnel than ever before within firefighting agencies, available to manage the expanding digital network associated with this Future State. With that said, the aim of this ConOps is to aid the existing agencies and organizations with new techniques and technologies, rather than simply suggesting expanding scope and personnel. Ideally, many of these new duties will fall in line with existing roles and duties or adapt existing roles and duties to increase efficiency. This ConOps does not foresee an impending need for an increase in “boots on the ground” aside from these paradigm shifts in data collection and communications methods.

7.4.2 Training

The future state outlined in this ConOps will require wildland fire personnel to use and operate new equipment and technology frequently during day-to-day operations. Expansion of a common training funding pipeline will thus be essential to the success of this ConOps. As mentioned earlier, this will largely take place within the scope of aerial operations as UAS become more heavily adopted, and in the mediums through which communications take place. Another area training will likely need to occur is in the assessment of new data in real time, especially if aerial drops and DVE operations become more precise and frequent. Personnel will be required to follow new procedures pertaining to these operations with the expectation of consistency.

7.5 Funding

To enable the desired, unified future state there is a need for a unified funding process, representing a fundamental departure from the current state. Through the research of this ConOps, it was made clear that funding is piecewise per local department within individual agency based on their requests from the previous year's projections. Not only is this setting the agencies up for failure, as projections cannot accurately capture anomalous years, but it also creates a feedback loop of continuous "catch-up" in all aspects of preparedness. Funding will not only need to increase in scope and prioritized in scale with the growing risk of wildland fires, but it must also be provided in a consistent basis that enables adequate planning with contingencies. Likewise, it should be equitable across all agencies and all departments such that there is not competition for assets.

7.6 Impacts During Development

7.6.1 Assessment of this ConOps

The following Section 8, Outcomes: Measures of Effectiveness discusses this impact in detail. Briefly stated, changes within the operations and organizations regarding collecting data in support of evaluating new technologies will be of paramount concern should this ConOps be adopted. To coordinate a potential paradigm shift in the wildland firefighting methodology cannot be taken lightly and has to show its worth as soon as it starts to be implemented, which means the proper avenues of data collection and analyses will be one of the first changes to take place.

8 Outcomes: Measures of Effectiveness

8.1 Overview

As it stands, this ConOps is just that, a concept. Should it be acted upon, how would the Wildland firefighting community determine its success? Furthermore, until it shows efficacy, this ConOps will not, and should not, see widespread adoption. In essence, there must be methods by which the effectiveness of any resulting firefighting activity brought about by this ConOps can be measured.

By definition, "effectiveness" implies the consideration of all possible scenarios from a comparative analysis, and therefore is a study of probability. Immediately, the world of statistics flagrantly presents itself. Which, to do justice in the discussion of new analytic techniques specific to individual wildland fire use cases, goes beyond the scope of this ConOps. Rather, this ConOps will discuss how a statistical research team may approach new measures of effectiveness, and the data they should collect in the upcoming fire seasons to form a sample of control.

The first step in formulating proper metrics is to ask what questions need to be answered by them. The overarching goal of these metrics should be to unequivocally determine if there is correlation *and causation* between the introduction of this ConOps and the total impact of wildland fires. In statistical terms, the null hypothesis, H_0, is that this ConOps has no effect on the total impact of wildland fires. This overarching null hypothesis can then be refined corresponding to the seven links of the wildland fire chain: Pre-Fire Active Mitigation efforts have no effect, Active Fire suppression efforts have no effect,…, so on and so forth.

While the hope is this ConOps would have a strong negative correlation with total wildland fire impact (reducing fire), the metrics should not have bias towards that finding, allowing for the possibility of a positive correlation (worsening fire). Likewise, any study or metric that claims a certain level of causation must be held to high accountability standards. This means they are ideally double-blind, and dependent variables such as weather, fuel levels, human intervention, demographics, time between ignition and detection, etc. are accounted for in an accurate manner through sufficient control studies and are reproducible. Equally important, given the risk wildland fires pose on the lives of real people, strict ethical codes of conduct should be followed, such as voluntariness, informed consent, and beneficence for any affected parties.

8.2 Big Data: Fundamental Variables

At first glance, it can sometimes be difficult to connect sophisticated metrics and analyses to their physical representation. In this sense, it helps to start from the ground up. All data information can be dissected into fundamental components – as a simple example, a single value of speed has both a distance component and a time component. Inherently, it is understood that to measure speed, both components are needed due to the physical limitations of measuring in the spatial and temporal domains with the final "speed" being a mathematical representation of the two together. Any variable that can be represented by a single, quantitative measurement (time, distance, dollars, personnel) or qualitative, categorical, and Boolean attributes (color, species, "true" or "false") are fundamental variables. There likely exist hundreds of fundamental variables in the wildland fire environment that can be collected, and indeed in any other complex discipline, which is why statisticians have coined the phrase "big data." "Big data" simply refers to all of these fundamental variables that get collected both actively and passively, before any analysis takes place. It is unfiltered, unprocessed, and gets collected indiscriminately and often very rapidly. It is an important first step, as these are the inputs into future metrics and models. Below is a non-exhaustive list of potential fundamental variables in wildland fire.

TABLE V
POTENTIAL FUNDAMENTAL VARIABLES IN WILDLAND FIRE

Data	Description	Type	Category
Flight Time	Total combined time airborne of all aerial assets	Time	Assets
Fuel Spent, Aircraft	Total combined fuel spent of all aerial assets	Volume	Assets
Fuel Spent, Ground	Total combined fuel spent of all ground assets	Volume	Assets
Injuries	Number of injuries that sideline personnel	Number	Assets
Number of Personnel	Total number of personnel assigned to incident	Number	Assets
General Demographics	Age, Gender, Race	Misc	Demographics
Land Ownership	Breakdown of land ownership within fire burned area	Boundary	Demographics
Mean Income	Average income of residents within area	Value/Area	Demographics
Mean Property Value	Average value of property within area	Value/Area	Demographics
Population	Total population	Number	Demographics
Population Density	Total Population/Area	Ratio	Demographics
Destroyed Structures	Total structures requiring repair due to fire incident	Number	Fire Status
Estimated total cost	Total cost of fire response and recovery efforts	Value	Fire Status
Evacuations ordered	Total evacuations ordered, by property	Number	Fire Status
Fire Duration	Total time fire was actively burning	Time	Fire Status
Fire Perimeter	Total distance around fire burn area	Distance	Fire Status
Number of Spot fires	Total fires in single complex; may be detached but related to main fire	Number	Fire Status
Wildland Fire Acres burned	Total area burned by fire incident since ignition	Area	Fire Status
Forestry Rehabilitation Acres	Total area requiring habitation and restoration after the incident	Area	Resiliency
Prescribed Acres Burned	Total area of a prescribed burn	Area	Resiliency
Species Count	Total number of each type of plant species in a rehabilitation area	Categorical	Resiliency
Air Humidity	Outside humidity, water vol/total vol	Ratio	Risk
Ambient Temperature	Outside temperature, weather	Temperature	Risk
Fuel Density	Average area per plant/total Area	Ratio	Risk
Fuel Flammability	Chemical makeup/vol	Ratio	Risk
Ground Gradient	Bi-Directional slope angle (topographic)	Vector	Risk
Ground Moisture	Water volume/total volume	Ratio	Risk
Ignition Point	Exact point of fire origin	Location	Risk
Recency of Burn	Time since last fire, prescribed or otherwise	Time	Risk
Risk Index	Fire risk index as defined by FEMA	Number	Risk
Wind Velocity	Wind speed with direction vector	Vector	Risk
Containment	Fire perimeter/total constructed fire line distance	Ratio	Tactics
Drop altitude	Altitude at which retardant or water is released	Distance	Tactics
Ingress distance, Aerial	Total distance of travel required by aerial assets	Distance	Tactics
Ingress distance, Ground	Total distance of travel required by ground assets	Distance	Tactics
Ingress Time, Aerial	Time from initial report to aerial assets on site	Time	Tactics
Ingress Time, Ground	Time from initial report to ground assets on site	Time	Tactics
Line Accuracy	Error of line centroid to requested location centroid	Distance	Tactics
Line Jumping	Did the fire cross over a constructed line, Boolean	T/F	Tactics
Line Precision	Ratio of spread to requested line	Ratio	Tactics
Line Thickness	Average distance fire would need to "jump" over a fire line	Distance	Tactics
Retardant Dropped	Total amount of fire retardant dropped for the incident	Volume	Tactics
Water dropped	Total amount of water dropped for the incident	Volume	Tactics

8.3 Types of Statistical Analyses

As with speed, these fundamental variables can be combined and manipulated in useful ways to gain further insight, draw comparisons, and make important decisions. Modern statistics builds on this methodology, wherein multiple variables are combined and/or weighted with a formula to create a new metric, or "score." New variables can even be created from these variables, which is called "feature generation." These new metrics are extremely valuable because they both summarize past behavior and results, and in doing so, indirectly predict future results. Simultaneously, the multi-variable nature absolves differences among the contributing variables, creating an inherently objective metric by which different subjects can be compared. This idea has garnered much attention in the sports and political disciplines, as teams and candidates constantly innovate better metrics to assess their competition despite the many different variables that impact success [366] [367]. Indeed, wildland firefighting can draw many parallels to other offensive-defensive formats.

8.3.1 Bayesian Search Theory

In the wildland firefighting discipline, a key component of quick response is accurately locating nascent ignitions, predicting high risk areas, prioritizing infrastructure resiliency and defense measures, and overall general quantification of the landscape and WUI. Bayesian Search Theory offers one method to do this [368].

The name comes from Bayes' Theorem in statistics, which describes conditional probability of an event occurring, given prior knowledge of the influencing conditions. In the case of a search mission, the initial conditions vary continuously over some area and in fact may likely change over time. This area can be discretized into a grid, with initial conditions assumed to be constant within each cell per time step, enabling a discrete probability calculation. With each cell having a unique probability score, a heat map emerges showing where the event is most likely to occur within the overall area, informing where to allocate resources per time step. As each cell is searched and conditions change, the resulting outcome updates the probability criteria for the rest of the grid, such that each subsequent "move" builds on the previous (this is formally referred to as Bayesian optimization). By predisposing that each cell searched results in the null (no discovery), a theoretical optimal search path is revealed iteratively [369].

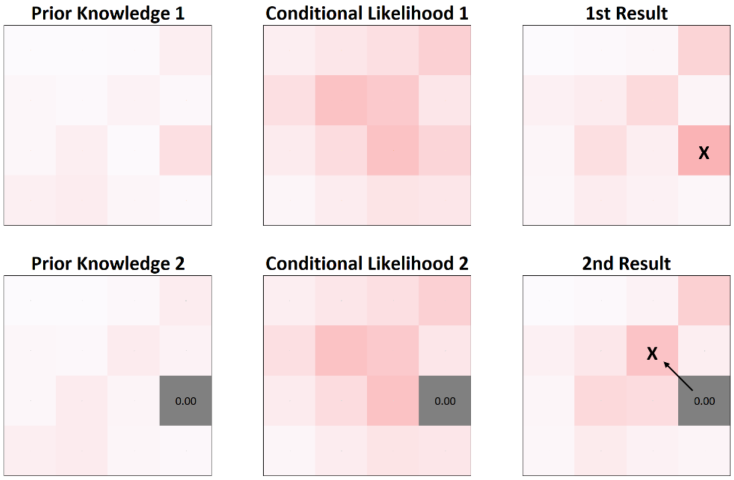


Figure 34. Simple Bayesian Search.

For the case of wildland fire, if a given region had a Bayesian grid for ignition risk, input conditions might be all the fundamental variables for fire weather. The resulting probability map would reveal the most optimal locations for a prescribed burn to reduce the area's overall probability below a certain threshold, while performing the minimal number of burns needed. For the same region, an entirely different Bayesian grid could determine areas of most risk from an infrastructure perspective. Inputs would be the fundamental variables for infrastructure and demographics, combined with topography, to inform firefighters of the most optimal initial attack to save personal property.

Indeed, this is essentially how FEMA creates its national risk index. However, more localized approaches could conduct a Bayesian grid assessment for smaller regions but at higher fidelities and compare the resulting paths generated using varying input conditions or optimization criteria. By comparing the overall grid scores and path criteria, separate regions and incidents can be compared in a quantitative manner. Importantly, a key component to having effective Bayesian grids would be the sample rate at which the initial conditions are updated to match reality. If this rate is on the order of days or weeks, the outputs would not be of much use to first responders and may only be applicable to long term planning solutions. If the sample rate were on the order of hours or minutes, a metric like this could potentially be lifesaving and integrate into the initial attack protocols.

8.3.2 Analysis of Variance and Co-Variance (ANOVA and ANCOVA)

An analysis of variance test, or ANOVA, is a statistical test in which a sample can be broken up by a categorical variable. By comparing the means of these sub-samples to the mean of the overall sample, an ANOVA can detect if there is a statistically significant difference in the contribution of a one sub-group somewhere in the overall sample. An ANOVA that detects a difference can be used to inform a test statistic (T-test) on each variable, which compares the amount at which each variable contributes to the mean, thus quantifying their variance. Likewise, an effect size (η^2) can tell how much that contribution explains the variance. Perhaps more useful and applicable to real world scenarios is the analysis of co-variance, or ANCOVA. This is essentially a more flexible and robust ANOVA, wherein both categorical and continuous variables can be evaluated together. In essence, when more covariates are included in the ANCOVA, the more the variation of the overall sample can be explained, and hence a statistical model can more accurately predict results. This is especially useful when a sample may have several contributing variables, such as two different wildland fires in different locations and months. An ANCOVA with subsequent T-tests could tell us if location played a role in the outcome, and if so, how much. Or likewise, how much total flight hours impacts how quickly a fire can be contained, while simultaneously correcting for location, weather, topography, etc. Additionally, ANOVAs and ANCOVAS can highlight the impact of dependent variables, such as ambient temperature and ground moisture, through an interaction plot, and the interaction itself can be evaluated for its significance. In general, both types of ANOVAs tell us how we should expect the mean to change, given a change in one variable, very similar to a linear regression. In this sense, an ANOVA can be thought of as a filter: it is a tool to help weed out variables that might not have an impact in the outcome [370] [371].

8.3.3 Linear Discriminant Analysis (LDA)

Linear Discriminant Analysis (LDA) is a useful method of prediction, where multiple variables combine to create a new “score” that determines whether or not an outcome is likely. Similar to ANOVA, LDA helps analysts cross-examine how different variables contribute to the outcome. However, what makes LDA useful on its own is that it positions the variables in such a way that the separation in their variance is optimized (maximizing the distance between means *and* minimizing scatter). By optimizing this separation, the more likely a prediction made using the statistical model will match reality, as there is minimal overlap in the variables’ new probability distributions. In this respect, LDA actually reduces the dimensions being analyzed, which is very valuable for applications where hundreds of variables impact an outcome. This is where the “Linear Discriminant” terminology comes from, as LDA utilizes linear algebra and eigenvalues to find that optimal separation [372]. Using an analogy and the figures below, this is as if a camera looking at the raw data was moved to some new, complex location such that reveals the bottom right figure. The power of eigenvalues, however, is this is not restricted to any physical representation and can operate in n-dimensions.

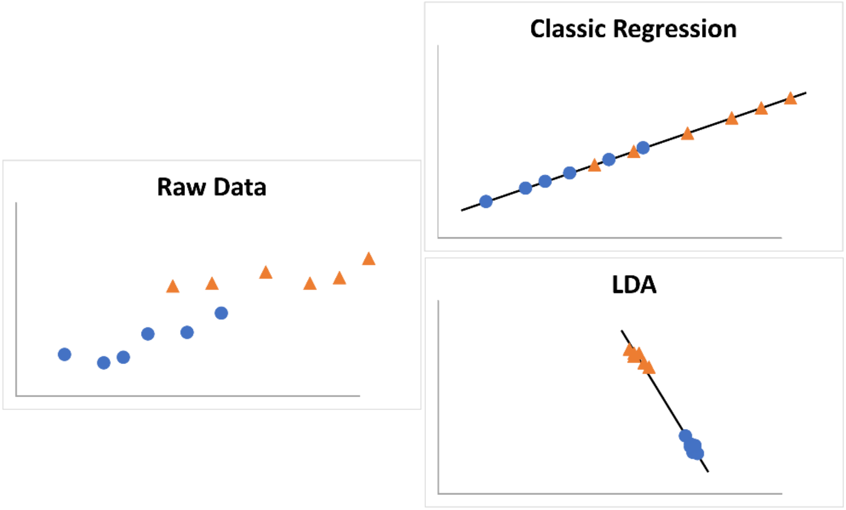


Figure 35. Example of LDA [373]

The best way to illustrate this is with a simple example: A real-estate firm wants to know the likelihood of a future neighborhood development being destroyed by a wildland fire. The two variables they are interested in are property value and proximity to an air tanker base. From their sample of historical data, they create a scatter plot with property value on the X-axis and proximity to a base on the Y-axis. They then mark properties burned with an X and properties unburned with an O. Within this scatter, LDA can reveal a line through the mathematically augmented data onto which the projections of all the X's are most separated from the projections of all the O's. Thus, this line is now the new axis from which the variables are analyzed from. Within this new view, two normal distributions, one for the X's and one for the O's, can co-exist with minimal overlap. Now, when a new data point is created (i.e., a new development), it is much more obvious as to which group it will most likely fall into, and thus the prediction will be more reliable.

8.3.4 Artificial Neural Networks (ANNs)

Modern data analytics, of course, involves computers and leveraging their capabilities to do the "heavy lifting" in analyses. Currently, "AI" captures most of the headlines about data, and while the term AI may be a bit of a misnomer, it fundamentally involves artificial neural networks (ANNs). ANNs are a very useful and capable tool for revealing patterns that even the most statistically savvy humans could not detect. Like the previous statistical methods, neural networks are useful for turning many different input variables into a single output result, and in turn can be utilized as both a predictor and method of comparison. However, what happens in between is created by the computer and is not necessarily known by the researchers. Instead, researchers provide a set of steps or rules, such as an algorithm or function, to the computer to assign weights, apply logic gates, transform, combine, interpolate, or otherwise augment the inputs. This creates new variables, called "features," which are simply new variables derived from the fundamental variables. Multiple steps can be added in series or parallel, depending on the intended result. In this way, a neural network sometimes is best represented as a schematic or flowchart. Often, there is also a recursive step where the algorithm updates the initial values with the augmented values and repeats the process to inform and change the coefficients, gains, or weights of the algorithm itself. This is why the development of a neural network is sometimes referred to as "training" [374] [375] [376]. An analogy would be a dynamic controls algorithm that could self-tune: where the final output error is minimized, but the algorithm was able to determine its own gains based on the previous dynamic behavior.

For this reason, a neural network may be the most sophisticated method of analysis in the wildland firefighting discipline due to its ability to handle a vast number of variables and detect patterns in a way far beyond human capability. They make it such that the colloquial bottle neck is now in the data collection itself, rather than the analysis.

8.3.5 Example

A great example of a novel attempt to provide quantitative data in fire suppression is from [91]. Here, the team determined that most fire decision making processes are subject to the discretion of the agency directors and

Incident Commander based on personal experience and knowledge of fire behavior in different conditions, as well as loose incentives, to minimize the ultimate cost. Therefore, their effort goes into quantifying the various steps in the decision-making process. This includes assigning values to various types of infrastructure based on their significance, various values for terrain (including roads and general ruggedness), weather data and fuel maps, and census data, to attempt to control for any decision-making bias. This is most similar to the Bayesian grid method, with some additional analysis on the back end. The team then overlays a simulation of an un-impeded fire originating from the same ignition point using commercial off-the-shelf fire simulators to compare the worst-case spread to the actual spread and determine a final score. While the team acknowledges many assumptions and areas for refinement, it is the first time any research has quantitatively shown that suppression efforts have a measurable impact on reducing fire spread — a method that could be applied and enhanced for future effectiveness analyses [165].

8.4 Methods of Control

As researchers perform these various statistical studies in the coming years, it will be imperative that they have some data to compare results to. While the actual analyses can be performed sometime in the future, the data of such control samples must be collected prior to the incorporation of this ConOps on the activities in which the analyses are performed, and it may be prudent to collect such data on real fires in the most forthcoming years upon its release. In other words, this data collection may need to be one of the first items implemented in a technical roadmap, as it will be difficult to determine with certainty when and where aspects of this ConOps appear in future data sets.

There are four avenues from which this data could be generated: simulated scenarios, live demonstrations, prescribed burns, and real wildland fires. In that order, each one increases in realism and risk, so researchers will have to weigh the desired fidelity with cost and safety.

8.4.1 Simulated Scenarios

A simulated scenario would exist entirely in a virtual world, on the computer. This would simulate a fire environment, either real or fictional, with precisely defined and controlled terrain, fuels, infrastructure, ambient conditions, and ignition source. This would operate like a digital twin with a physics engine and rendering capability, to analyze various scenarios and situational tactics. Importantly, the fidelity and computational cost of the simulation would play a large role in the data able to be extracted. Likewise, the decision-making process and logistical impacts of real-world tactics and human factors would have to be extremely well known to accurately model in a virtual manner, which is a major challenge. For this reason, a simulation, while low risk, would likely be an insufficient data source alone in the near term.

8.4.2 Live Demonstrations

A live demonstration would involve a real, confined area of precisely defined and controlled terrain, fuels, infrastructure, ambient conditions, and ignition source. This would operate much like any laboratory test, such that fire could be observed and tested in both an unrestricted state and with suppression efforts. As new suppression efforts are added, this "scenario" can be ran multiple times to see the outcome. Importantly, real sensors would need to exist and be verified and validated (V&V) prior to a live demonstration, and indeed this will be the case for each level of test realism hereafter. A challenge to this method would be to find enough space to repeatedly burn in a way that matches a wildland fire, at the rate required to collect a large enough sample size. Furthermore, the destructive nature would be a hurdle to get stakeholder buy-in, which would likely mean these would quickly reduce in both physical size and relative scope.

8.4.3 Prescribed Burns

Prescribed burns perhaps offer the most cost-effective and realistic avenue for data collection. This would involve simply setting up the necessary sensors and getting approval from the burn boss to be included in the burn plan. Because there is already widespread support and knowledge on the benefits of prescribed burns, these are likely to happen at very frequent intervals and be accommodating of data collection. Likewise, because prescribed burns occur in real ecosystems, these would be as close to a real fire as possible while still being controlled. A challenge to this would be to incorporate suppression strategies, as the intent of a prescribed burn is fuels reduction. Furthermore, requesting larger assets, such as tankers could be seen as a waste of resources. In this sense, a data collection prescribed burn may have to be procedurally separate from a fuel reduction prescribed burn, treating it as a training event. Land designated for a standard, fuels reduction prescribed burn could be nominated for a data collection prescribed burn, thus increasing the scope and number of assets devoted for the sake of this data collection while being mutually beneficial.

8.4.4 Real Wildland Fires

Certainly, if and when a wildland fire occurs, there is merit in collecting data on the incident as discussed in Sections 4 and 5. However, this method shall not be relied upon as the only means for data collection due to its inconsistent, infrequent, and destructive nature. Additionally, the ethics involved become a bit more complex as data may have restrictions due to land ownership, personally identifiable information, and proprietary control.

8.5 Data Ethics

A critical component of any discussion on data collection and statistical analysis is that of ethics. Indeed, as more and more techniques are available to researchers to be creative and extrapolative with their analyses, so too are there more ways to force a particular outcome, be it intentional or not. Any study should be met with scrutiny and provide a means for other research teams to verify the efficacy of a finding by conducting the test themselves and reaching the same conclusions, all the while respecting any participants of the study.

8.5.1 P-Hacking

One of the first variables a statistics student learns is the P-value. This is a number, or percentage, that corresponds to the probability of a particular outcome occurring. There are many different probability distributions in statistics, each with various analyses, but basic statistics can be summarized as assessing a single P-value or comparing different P-values. While these probabilities are good indicators of an outcome, they often represent a sample as opposed to a population, and therefore carry some amount of error. This error can be thought of as a gray area in which an array of valid solutions exist together. When pairing that with an explicit cutoff for statistical significance, two identical studies can reach opposing conclusions, even if the work conducted was valid. This error can be unintentional due to a lack of diligence in setting up the study, imparted subconsciously through bias, or intentionally included in the design of the study because a result pays the bills. This manipulation of the resulting probability is referred to as “P-hacking” and even extends beyond just probabilities. P-hacking is the colloquialism for any statistical malpractice which jeopardizes scientific integrity. Any study conducted must be aware of this possibility and include proper sample sizes and control studies. The best way to catch P-hacking is through peer review and reproducibility [377] [378] [379].

8.5.2 Reproducibility

Reproducibility, as the name suggests, is the ability for a study to reach the same conclusion, regardless of who and when it is conducted. This means it has properly accounted for all variation and error in the model, and results are presented as transparently as possible. This includes methodology that is realistic, such that any genuine attempt to reproduce results is possible. It shows good faith and diligence in the original study, in effect proving non-bias. While in theory, peer review can occur on a written report alone, reproducibility is necessary for peer review to reach unequivocal and widespread acknowledgement in the community, and an inherent requirement for commercial applications [380].

8.5.3 Voluntariness, Informed Consent, Beneficence

Any study that uses people or their property for data collection must also be held to high standards of ethics. Three of the most common concerns in this regard are voluntariness, informed consent, and beneficence, which are most notably defined in the Belmont Report [381]. Voluntariness means that participants are not coerced in any way to participate in the study, nor are their responses influenced by external pressures. Likewise, they are free to rescind their participation at any time before, during, or even after a study has been conducted. Informed consent means that participants are fully aware of their right to voluntariness, and that the entire scope of their participation is disclosed ahead of time in order to make an informed decision to participate. This importantly does not mean elements of a study, such as blinded-ness, need to be disclosed, but rather, the procedures or environments to which the participant will be subjected. Beneficence means that the goal of the study ultimately aims to benefit the participant in some way, and researchers ultimately want what is best for everyone involved.

For the case of wildland fire studies, data will certainly include real lives of people and their property. Therefore, all three of these ethical concerns must be required of any study that utilizes information that does not fall under the public’s domain.

9 Analysis of Proposed System

Discussed in detail in *Section 9 Analysis of Proposed System,* below is a summary of all the proposed changes for quick reference. While this ConOps lays out a framework that is intended to better the overall wildland firefighting discipline, it certainly will have its challenges. This ConOps recognizes that no one solution will perfectly align to every problem in every fire, and many ideas presented have pros and cons. Indeed, there are aspects of fire that have such a dynamic and complex nature, there are simply infinite ways an event can unfold – even the best plan must be adapted to fit each scenario. To that end, some of these trade-offs are also discussed below, with a description of the thought process, research, and justification of the selected methodology. Through identification of the weaker points and areas of limitation in this ConOps, implementors can design redundancy and contingency measures and manage expectations.

9.1 Summary of Improvements

9.1.1 New Capabilities

New capabilities are items that are completely novel to the wildland firefighting discipline and will likely involve training or other learning to incorporate into standard procedures.

TABLE VI
NEW CAPABILITIES OF WILDLAND FIREFIGHTING

Component	**Section**	**Area of Impact**	**Description**	**Phase**
Common Operating Picture	5.7	General	Unify all future state changes into a common operating picture for situational awareness and interoperability in an easy to digest and visualize format	All
Data Analysis	5.8.1	Pre-Fire-Year Review and Risk Assessment	Integrate new programs and equipment needed to view and understand the data, such as machine learning and digital twins.	Pre
Prescribed Burn Risk	5.8.2	Pre-Fire Active Mitigation	Introduce new tools, such as the "BurnBot" or aerial drones, to minimize negative impacts and risks of prescribed burns.	Pre
Fire "Diamond"	5.8.2	Pre-Fire Active Mitigation	Inclusion of activity that influences fire behavior and effects, as opposed to ignition only, changing fire triangle to a diamond.	Pre
Data Analysis	5.8.3	Dynamic Pre-Fire Risk Assessment	Add new connections, processes, and tools with real time reaction to rapidly changing risk levels	Pre
Detection Components	5.9.1	Ignition Detection	Introduce new detection tools, such as HALE UAS, AI/ML, or increased data storage; and new standards for uniform detection thresholds.	Active
Strategic Placement	5.9.2	Initial Attack	New infrastructure for localized UAS stations based on risk level, as noted in 5.8.3	Active
Airspace	5.9.2	Initial Attack	Develop new low altitude rapid response corridors	Active
Suppressant Effectiveness Measures	5.9.3	Extended Attack	Introduce new methods of measuring suppressant drop effectiveness, such as wetted area burn through.	Active
Precision Mapping	5.9.3	Extended Attack	Introduce methods of precision mapping of fire perimeter and behavior for real-time assessment and resource allocation.	Active
Airspace Management	5.9.3	Extended Attack	Introduce far-edge and near-edge electronic position and vector awareness tech via V2V2I in UAS.	Active
Remote Sensing	5.9.3	Extended Attack	Introduce data standards with federated learning to increase data sharing.	Active

9.1.2 *Enhanced Capabilities*

Enhanced capabilities are items that already existed prior to this ConOps, but would be augmented and improved in some way, whether by increasing efficiency, success rates, or safety, or otherwise reducing cost. This will likely be most technological capabilities due to the foresight necessary to predict and incrementally incorporate a maturation roadmap.

TABLE VII
ENHANCED CAPABILITIES OF WILDLAND FIREFIGHTING

Component	**Section**	**Area of Impact**	**Description**	**Phase**
Data Security	5.7	General	Utilized "Zero Trust" mentality in data security measures when using data of increased scope, fidelity, and inter-connectivity	All
Cultural and Organizational Considerations	5.7	General	The must be a mutual understanding and respect that new changes will augment traditional and cultural norms within the firefighting community, and neither should be a hinderance to the other.	All
Restoration and Stabilization	5.10.1	Recovery	Utilize the tools and technologies created in the other parts of the wildfire chain to better predict, model, and collaborate on new restoration and ecological strategies.	Post
Focus	5.11.1	Organizational	Shift focus on budgeting and equipment from only suppression to an even spread across the entire chain.	All
Structure	5.11.2	Organizational	Increase technical support and research within the wildland fire agencies with an overarching R&D executor to bring together the currently lacking and otherwise fragmented technical development.	All
Funding	5.11.3	Organizational	Increase funding to meet the commanded need of wildland fire reduction and support the necessary technological developments.	All
Culture	5.11.4	Organizational	Increase interagency forums, discussions, and trainings to foster new solutions and reduce the anxieties surrounding safety and time when introducing these.	All
Collected Data	5.8.1	Previous Year Assessment	Increase fidelity, make digitally available, and update frequently and dynamically.	Pre
Resource efficiency	5.8.1	Pre-Fire-Year Review and Risk Assessment	Increase interagency collaboration and cooperation.	Pre
Collected data	5.8.2	Pre-Fire Active Mitigation	Increase fidelity, make digitally available, and update frequently and dynamically.	Pre
Strategizing and Prioritization	5.8.2	Pre-Fire Active Mitigation	Utilize AI/ML for strategizing and area prioritization.	Pre
Human Activity	5.8.2	Pre-Fire Active Mitigation	Increased emphasis on assessment and creating mitigation strategies	Pre
Data Analysis	5.8.3	Dynamic Pre-Fire Risk Assessment	Increase fidelity, decrease latency, and focus scope to hyper-local conditions	Pre
Detection Components	5.9.1	Ignition Detection	Unify all ignition detection platforms into an interconnected system that can share data and enhance computing capabilities.	Active

Envelope Expansion	5.9.2	Initial Attack	Incorporate uncrewed UAS to expand the operational envelope in DVE's with the appropriate sensors for situational awareness and airspace integration, as well as payloads for suppression activities.	Active
Aircraft Utilization	5.9.3	Extended Attack	Incorporate uncrewed and optionally piloted rotary aircraft to expand the operational envelope in DVE's for both suppression efforts, resupply missions, and emergency personnel extraction.	Active
Tactical overwatch	5.9.3	Extended Attack	Incorporate UAS for command-and-control missions using various sensors for personnel situational awareness.	Active
Remote Sensing	5.9.3	Extended Attack	Continued advancements in UAS and sensors to increase data fidelity.	Active
Common Operating Picture	5.9.3	Extended Attack	Increase collaborative approaches through smart phones, apps, and AR for in-field firefighter input and situational awareness.	Active
Persistent Connectivity	5.9.3	Extended Attack	Utilize a system of systems approach to increase connectivity within existing infrastructure and new infrastructure with redundancy.	Active

9.1.3 Removed Capabilities

Removed capabilities are items that this ConOps renders obsolete. This can be due to replacement by new capabilities, or because they are deemed as a hinderance to the overall mission such that removal increases efficiency, safety, and success or reduces cost.

TABLE VIII
REMOVED CAPABILITIES OF WILDLAND FIREFIGHTING

Component	**Section**	**Area of Impact**	**Description**	**Justification**	**Phase**
Fire Triangle	5.8.2	Pre-Fire Active Mitigation	Replacement of the classic fire triangle with a diamond to include human factors.	Implies human activity is unrelated to wildland fires. In reality, it is a crucial part.	Pre
Airspace Management	5.9.3	Extended Attack	Remove current RID systems in UAS.	FAA's broadcast network renders ineffective for precision positioning and ID of UAS.	Active

9.2 Disadvantages and Limitations

9.2.1 Overview

While this ConOps aims to address all identified shortcomings across the scope of wildland firefighting, some of these gaps will not be fully closed, and some are not feasible with humanity's current understanding of nature and physics. A disadvantage is an attribute of this future state concept which a different concept would be able to do more effectively, safer, or cheaper, and often is associated with some trade-off. A limitation is an attribute of this future state concept that despite best intentions remains a challenge or hurdle, such that any other concept would likely also have this challenge. This would often be associated with a technical gap or fundamental lack of understanding, and are areas that may be worth further, detailed research. However, this ConOps is intentionally general such that derivative concepts can utilize the findings to fulfill more specialized design criteria. Therefore, many potential disadvantages are accounted for by offering multiple options on either side of a trade, as discussed in *Section 9.3 Alternatives and Trade-Offs Considered.*

9.2.2 Disadvantages

9.2.2.1 City Planning, WUI, and Demographics

Although this ConOps acknowledges the roles these components play on the wildland firefighting discipline, it fails to address new methodologies and criteria for the design and development of new cities and the impact on demographics in a region. Moreover, this ConOps assumes that over a large enough area, such as the United States, local variation will become more homogeneous and therefore a generalized concept will see some success across different localities. A different concept, however, could see significant success in individual localities if these effects are taken more into account, tailor made to find bias, building code shortcomings, and specific areas where there is significant WUI overlap. Further, the concept of demographics and city planning opens the door to auxiliary, yet equally complex challenges in economic distribution, and social justice reform that simply goes beyond the scope of this ConOps.

9.2.2.2 Hybrid Electric, Electric, and Solar Aircraft Technology

A consequential sub-discipline of aviation is the work being done to find alternative fuels and power generation that are both sustainable to the environment and economically viable. This ConOps assumes that is inherent to any new UAV design study and does not select a desired UAV power generation method, especially for different missions. However, this selection could have huge implications on overall system cost, infrastructure requirements, and community adoption based on the perceived learning curves, safety considerations, and environmental impacts that fuel type has on maintenance, flight performance, and safety. An alternative concept that makes a selection for each mission type within the near, mid, and far terms could be more easily justified for adoption thanks to more thorough expectations. With that said, the associated technology roadmap to this ConOps addresses some of these milestones.

9.2.2.3 New DoD Branch: Wildland Fire

One idea that is often suggested in one form or another is to create a new branch in the miliary specifically for wildland fire. Indeed, in an ideal world this would solve a lot of the jurisdiction and resource issues seen in the current state. However, this ConOps does not specifically address this idea to 1) Allow for near term solutions utilizing existing infrastructure 2) enable utilization outside of the U.S. as appropriate 3) allow for creative thinking and flexibility as this document ages. Perhaps the last point is most important, this document should stand the test of time and not pigeonhole itself to one methodology. Likewise, this ConOps aims for incremental wins, whereas this solution, while intriguing, is rather grandiose and may take years to implement effectively which wildland fire does not have.

9.2.2.4 Ground-Based Mechatronics, Bionics, and Biometrics

While much of this ConOps focuses on the aerial component of wildland firefighting suppression due to NASA's expertise, technology can certainly play a major role on the ground. This can be in the form of small, fire-resistant robots to perform terrain mapping, fuels monitoring, or even collect flame performance data, or larger robots for tactical logistics such as equipment transport or re-supply missions. Likewise, new suits and armor could be designed for firefighters to reduce the physical burden in a harsh environment, and biometric devices could continuously monitor their health and location status for situational awareness. These items are glossed over in this ConOps as "general technology improvements" again for the sake of general application. Another concept could certainly envision very applicable devices to augment the work being done on the ground, like the BurnBot mentioned in *Section 5.8.2 Pre-Fire Active Mitigation*.

9.2.2.5 Environmental Recovery and Restoration

A major component of ecosystem health is in the recovery and restoration of wildlands and watersheds, as discussed in *Section 4.* However, this ConOps does not go into too much detail about new methods and changes to implement in the specific discussion of wildland fire. Largely, this is due to the significantly longer timespans of ecosystem restoration (decades) relative to that of fires (years). Likewise, discussion of ecosystem health by and large would require significant discussion on climate change and its effects, which simply goes beyond the scope of this ConOps. However, effort in these areas would in fact have profound impacts on reducing wildland fire severity, and an alternative concept that includes this to full justice would see great success.

9.2.3 Limitations

9.2.3.1 Fire Modeling and Virtual Training Environments

While the science of what causes fire, and chemical makeup of fire is very well known, simulating it in a scientific way is a challenge that will likely not be solved for some time due to the complexity of contributing factors and lack of fundamental model from which to solve discrete parameters in a computationally efficient way. A potential future state of fire modeling could envision a level of fidelity similar to that of a hypersonic plasma CFD simulation. That is, a fire model would need a set of equations that incorporates the chemical makeup of fuel, micro-climates, topography, and infrastructure at sub-acre resolutions, in addition to weather and atmospheric conditions up to at least 20,000 feet that could be discretized and converge on a solution. Indeed, approximations could get a significant amount of accuracy, however it will always be an area that could be improved upon. Similarly, an environment that is entirely digital could substantially boost the data collection, training, and strategic methodologies from a statistical simulation standpoint, and is worth further development. However, the computational cost and level of detail required before useful information could be gleaned will take a significant investment. However, that investment would likely be dependent on some level of proof of concept. Therefore, this ConOps marks this as a subsidiary of remote sensing to develop better models in the future state.

9.2.3.2 Precise Ignition Detection

Much like fire modeling, the accuracy and precision of fire ignition detection methods will always be an area that could be improved upon, as there will almost certainly never be a system that does not require a human to confirm that a fire has ignited. It is possible to make better and better predictions, with better and better sensors more densely placed, but even in the future state of this concept, humans are the final arbiter in the dispatch authority.

9.2.3.3 Alternative Suppressant Research

There may or may not be new and alternative ways of suppressing fire that have not yet been discovered or designed. This can be chemically, such as existing fire retardant, or physically, such as water and other “snuffing” approaches. While this ConOps assumes that the current materials and methods are very good when used correctly and will remain the staple for many years into the future state, it is possible that a new medium could be researched in the sake of making suppression efforts more efficient. Some key traits would be density, viscosity, retarding performance, environmental impact, toxicity, permanence, etc. In combination with advances in fire modeling and the understanding of the quantum behavior of fire, the distant future could see new methods of suppression that are simply not plausible today.

9.3 Alternatives and Trade-Offs Considered

9.3.1 Overview

Several of the trade-offs considered whether the benefit outweighs the risk of introducing new methods or technology into an already high-risk environment where the margin for error is very narrow. In general, this ConOps assumes the methodologies proposed will foster a net benefit to the overall wildland firefighting mission, although it recognizes the valid concerns raised in the interim. Therefore, a few of the largest examples are discussed below to supplement the discussion in *Section 5*.

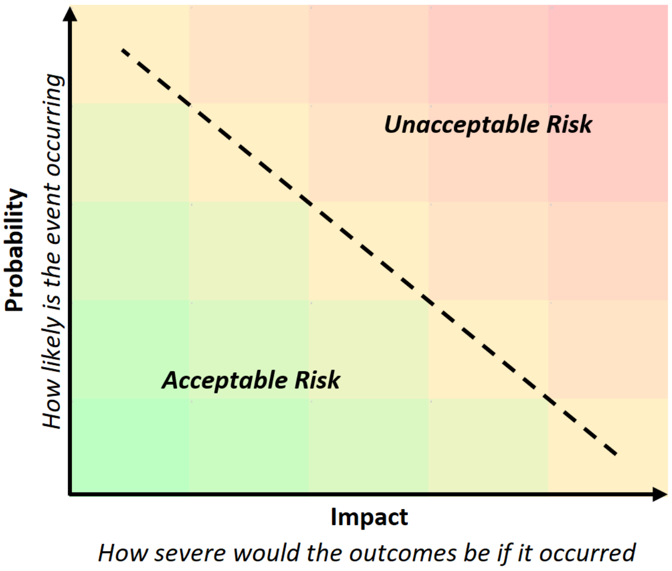


Figure 36. General Risk Matrix.

For each of the following scenarios, the tradeoff can be summarized by a risk matrix. Every operation fits into this matrix, which cross-analyzes the probability of an event occurring with its resulting severity. While risk can never be fully absolved, and indeed risk aversion can be a hinderance in and of itself, risk reduction efforts have these two points of control to move the event as much into the green as possible. Sometimes the outcomes remain severe, and the only way to reduce risk is to reduce the probability of the event occurring. However, this matrix is helpful because it provides a spectrum of risk acceptance rather than a yes or no. Sometimes, changes may not require an absolute, such as grounding aircraft during DVEs, but rather a change in tools or procedure to nudge the risk to the neighboring cell, taking it from an unacceptable risk to an acceptable risk.

9.3.2 Prescribed Burns

To some, the adage “playing with fire” rings true in the topic of prescribed burns. No fire is controllable in the absolute sense, which is why prescribed burns have been met with push back and controversy as their utilization increases to correct the negative trend of wildland fire. This is no thanks to the occasional instances of a prescribed burn breaking contingency measures and escalating into an uncontrolled wildland fire, or the negative effects of smoke and emissions to nearby communities. This ConOps assessed the following trade-off: the benefit that fuels reduction via a prescribed burn has on the overall wildland fire risk in a region, versus the cost and risk of a prescribed burn becoming uncontrolled as well as its negative effects on neighboring communities from smoke and emissions.

Comparing the risk of a prescribed burn to the risk of a wildland fire is difficult due to the different timescales and areas involved. It plays off the biases humans have when assessing risk: the probability that a wildland fire would have ignited in the exact area without a prescribed burn within the next 6 months is relatively low, so the risk of a prescribed burn becoming uncontrolled is disproportionately weighted as more significant. However, the probability of a wildland fire igniting somewhere in the vicinity in the next 5 years is relatively high; it’s simply perceived as distant (in time) enough to label as low risk. When a fire does occur, the timeline to prepare is gone, and suddenly it becomes prudent to have areas with already low fuel levels, which may not have been on the community’s mind 3 or 4 years prior.

While in the short term a prescribed burn is proactive, in the long term it is in fact reactionary due to oversights in zoning plans, increased WUI, and lack of ecosystem management that compound over years and decades. However, prescribed burns remain an effective way to reduce fuel quickly and should not be abandoned entirely. They act as quick way to bring an area of significantly high risk to significantly low risk, especially where there are high volumes of human activity. Furthermore, if a wildland fire were to start elsewhere in the vicinity, the prescribed burn area would impede the progress and immediately contribute to the containment of the fire, saving time and resources. Over a population, evenly distributed fuels reduction lowers the total risk, and increases the probability of a fire being contained before becoming a major disaster.

Certainly, a prescribed burn has its faults. Nor does this ConOps present it as the only solution. This ConOps determined that the risk associated with a prescribed burn becoming uncontrolled can be actionable and mitigated using techniques employed in the future state, and likewise for the effects of smoke, such that its benefits outweigh the risk. It also assumes that one or two megafires produce more smoke and hazardous emissions than an average years' worth of prescribed burns for a given region and is a small price to pay for the long-term ecological health. This can be complimented by education on the realized risk of prescribed burns and how it is part of a larger picture in protecting the community at longer timescales.

9.3.3 DVE Operations

The name alone, *degraded* visual environments, implies non-ideal conditions, and therefore carries an increased risk compared to the alternative. Currently, DVE's ground all aerial assets without exception for pilot safety. However, as noted in *Section 5*, aerial operations are only active for approximately 8 of the 24 hours in a day which happen to coincide with a time period when a fire is most likely to have aggressive spread. This ConOps assessed the following trade-off: the benefit of increasing aerial operations in DVE's when fire is in its mildest form, versus the risk and cost of pilot and personnel safety. This ConOps acknowledges this is an exceptionally important area of safety that must be upheld, and personnel safety must be paramount above all else.

Unsurprisingly, suggesting expanded flight operations during these times is a challenge and can only occur with the same or higher level of confidence and safety that the current operations have grown accustomed to. Therefore, this envelope expansion will require augmentation with new or enhanced tools that lower the risk level to counter-act the increase in flying during DVE conditions. In the risk matrix, augmented piloting capabilities can lower the probability of a crash, or remote piloting can lower the severity of crash since it would be uncrewed.

Furthermore, it is assumed that increased operations have a compounding benefit, with an exponential greater than 1. For example, if the envelope is expanded to 16 hours out of 24 (a 33% increase), that will result in at least an equivalent reduction in overall cost of the fire, due to fire spread being a rate of area increasing with the square of time. For this point alone, this ConOps marks DVE operations as a key component in the future state, and assumes the benefit far exceeds the increased risk.

9.3.4 UAS Operations

Similar to DVE operations, UAS operations deserves a brief discussion regarding valid concerns associated with any vehicle that is uncrewed. This ConOps assessed the following tradeoff: the benefit of flight envelope expansion and logistical capabilities of UAVs versus the increased risk in situational awareness and communications inherent to being uncrewed.

Uncrewed vehicles, especially aircraft, have gained much popularity due to their removal of the human from the environment. Not only is this in the case of a catastrophic failure and crash, but also in the aircraft performance, handling, and design. For example, an uncrewed aircraft allows for significantly increased payloads simply from a weight perspective. They can also fly much more aggressively and precisely without needing to keep G-loading under instantaneous and sustained limits that are fatal to humans. In combination to relative technological advancement in guidance, navigation, and control (GNC), materials, and computational analysis tools, UAV's have become very well suited for tactical environments to carry out tasks that are high risk for humans. Conversely, there are valid concerns to be raised by this, such as situational awareness and communications between crewed and uncrewed aircraft. UAV's do not fly in an isolated environment and must not be blind to the surrounding airspace. At a minimum, they should have a human-controlled override feature and failsafe's such as geo-fences for redundancy in extreme cases.

Much like DVE's, this ConOps treats safety of personnel with paramount concern. Therefore, any inclusion of UAV's must be associated with new tools and technology to counteract any increases in risk such that the safety and confidence currently enjoyed is met or exceeded. This ConOps either includes or assumes these tools are part of the future state, such as geo-fences, COP, and remote sensing. Additionally, because UAV's can either be fully autonomous or simply remote-piloted, there are options to fit each niche and in fact allow for UAV's to be included as technology to assist in other areas of risk reduction, such as prescribed burns and DVE's. Likewise, the risks associated with the inclusion of UAVs are known and actionable, and do not further put the lives of personnel at risk the way a crewed mission may. To this end, this ConOps believes UAVs have a benefit worth pursuing and troubleshooting for use in the future state.

9.3.5 Increased Data and Connectivity vs. Information Security

One topic that is the unsung hero in the digital age is data and information security (IS). When it works, it goes unnoticed; and when it doesn't, entire systems can collapse. It is the pillar that society relies on, thanks to the hard work over the last few decades in digital cryptography. As with all disciplines in the topic of security, it requires vigilance due to the "cat and mouse" nature of security measures versus bad actors. Indeed, this ConOps cannot envision a future state with a profound increase in data collection, analysis, connectivity, and interoperability without an equivalent increase and allocation for the corresponding IS that that requires. This is underscored when considering that most of the entities involved in the wildland firefighting space are government agencies. Rather than accepting the risk or determining the benefit outweighs the risk, this ConOps agrees that this is a required corollary to the future state of data. In essence, this is a required part of data and the future state.

9.3.6 Conventional vs. Vertical Takeoff and Landing Aircraft

Shifting the discussion of trade-offs from one of cost-benefit to one of design requirements and operational use, a major question in aviation is whether an aircraft should be vertical or conventional takeoff and landing (VTOL and CTOL, respectively). This ConOps assessed the trade space for when each design is appropriate.

VTOL aircraft exist due to their ability to theoretically take off and land anywhere. Even the smallest runways can be nearly a mile long, while the largest runways reach almost 2.5 miles. Especially in tactical environments, removing the need for a runway entirely is a huge advantage. They can hover or change their azimuthal orientation without forward motion, making VTOL very handy for missions that require tight maneuvering, or staying above a specific location for extended periods of time. The vertical capability has some interesting impacts to the design of these aircraft, however. Most importantly, the power plant (engine) is used for spinning one or more rotors to generate lift, whereas conventional aircraft use it to create forward motion. Because of gravity, the former requires much more energy to overcome, so rotors become very large relative to the size of the aircraft. For forward flight, a helicopter pitches down slightly, such that the vector of lift points with a slight forward component. Counterintuitively, all propellers and rotors create drag even when spinning, and can be approximated as a large flat disc. For both of these reasons, VTOL aircraft are weight limited and have severely restricted endurance.

Another major consideration when operating a rotary VTOL is rotor wash. To fly, a VTOL must displace at least the same mass of air as the mass of the aircraft, which all gets directed downward. In dusty areas, or areas with lots of debris on the ground, this can create an unsafe environment for personnel in the vicinity. While there is less area required, landing locations still must be carefully selected and perhaps prepped by wetting or removing debris. Furthermore, because the density of air decreases with altitude, VTOL aircraft lose performance the higher they fly, and ultimately have a low flight ceiling compared to conventional aircraft. This becomes a factor in mission planning, especially in mountainous terrain with high elevations. Another component of VTOL is that large rotors are more likely to strike nearby obstacles due to drifting while in a hover, or temporary lapse in pilot judgement because the high revolution speed of the blades makes them difficult to see. Typically, this creates a catastrophic failure of the blade and prevents further lift generation. Another major design consideration in VTOL is that of gyroscopic procession, which makes GNC and flight dynamics particularly tricky. The large spinning mass that is the rotor creates a gyroscopic moment, which for VTOL is most aggressive in yaw. This must be counteracted with a secondary rotor, either on the tail to create an equivalent opposing moment via propulsion, or as an identical rotor operating in the opposite direction such that the two gyroscopic moments cancel out. The second method is perhaps most common in small camera UAVs, or "quadcopters." However, this gyroscopic moment also impacts the flight dynamics when maneuvering, so controls for rotary aircraft must consider this in addition to the aerodynamics of the blade within each revolution.

Conventional aircraft, on the other hand, are contrary to much of the above. They generate lift by increasing energy in the forward direction, as opposed to rotational direction. As mentioned, this means they need a long, flat area to transition between the high energy of flight to low energy of taxiing. Further, to maintain lift, they must always have this minimum forward energy to have airflow over the wings, otherwise the conventional aircraft will stall. For any mission above a single point, this means they must orbit rather than hover, which takes more fuel in the long run. However, because gravity is only in the vertical direction, this forward energy is much more easily attainable and sustained through momentum. Plus, without the large rotor, conventional aircraft can be designed to have much more aerodynamic bodies. Combined, this means conventional aircraft can be larger and faster than VTOL aircraft, making them ideal for movement across great distances at higher altitudes, and for large payloads.

Another application of VTOL is in hybrid airships, which create lift through buoyancy rather than pressure differentials created by some induced velocity. This means they can benefit from the flexibility of VTOL while also being highly power efficient, because no propulsion is needed for lift, just enough to overcome drag. Such applications in wildland fire would be tactical overwatch, command and control, or communications nodes. They could also serve as logistical vehicles for ingress and egress of personnel or equipment. Two of the biggest technical challenges to airships, and why these are seldom seen in any aviation application in the current state are in the acquisition of lighter-than-air material, as well as the methods of ballast when payloads are released. For example, if an airship has the right buoyancy to carry, say, a tanker's worth of fire retardant from a tanker base to the fire, once that retardant is deployed, the airship will want to rise. Currently, helium and hydrogen are the two chosen materials, which are both rather expensive, so the cost alone makes them difficult to acquire and want to bleed off upon payload deployment. Advanced airship designs explore compression and expansion methods to modulate the buoyancy, although this quickly becomes more expensive than a well-known rotary UAV design. This ConOps therefore does not pursue the hybrid airship avenue further and assumes rotary UAVs will remain the most viable option for VTOL.

In the scope of wildland firefighting, much of this is well known. Where it will play an important role is in the design of new UAVs. With higher g-loading and advanced avionics, UAVs can easily address or circumvent the various challenges with VTOL, and CTOL is more or less trivial given an adequate runway. However, wildland fire fits a perfect niche of requiring both large transport of personnel, equipment, or suppressants, and high maneuverability with applications for hovering requirements. While this can certainly be addressed with two different aircraft with different missions, and indeed that will likely occur in the nearer-term future state, an up-and-coming aircraft is a hybrid of the two. The HVTOL looks like a cross between a conventional aircraft and a helicopter, with a short, stubby wing capped with two large contra-rotating rotors that pivot along the wing axis for transition from vertical takeoff and landing to forward flight. In slow forward flight, it generates both lift and forward propulsion from the rotors, which have a forward cant. In fast forward flight, much of the lift is generated by the wing and the rotors supply mostly propulsive force. The most famous example of an HVTOL is the V-22 Osprey, although the future state envisions aircraft more closely resembling the up-and-coming hybrid air taxi concept seen in private industry.

9.3.7 Change vs. Cultural Norms

While less technical, a valid consideration and trade-off that will need to occur in the future state revolves around the dichotomy between wanting new tools, processes, and adaptations to the dynamic environment of wildland fire, with the general human nature of resisting change. Indeed, this can be thought of as a cost-benefit as some of the previous tradeoffs, however this ConOps treats it as separate due to the interpersonal and qualitative attributes: it is much more difficult to convince someone of a certain feeling in an ethical way than it is to convince them of simple arithmetic.

The wildland firefighting community has decades of experience with contemporary technology, as well as a comradery rooted in generational legacy consisting of entire careers and life-long dedication to the craft, trials and tribulations that includes the loss of human life, and an overwhelming pride in selfless duty of going into harm's way to save lives. While not intentional, the introduction a new tool or process risks the implication that the current method is either wrong or not good enough, thereby invalidating the very essence of firefighting. It is a symbol and representation of traditions that new actors in the discipline shall not be ignorant to, or they will seldom see adoption. This ConOps recognizes this to the fullest extent, and thereby recommends that new tools and processes are to be presented as enhancements and augmentations to *assist* firefighters in their duties, rather than replace.

In this respect, an appropriate methodology to impose is "risk communication" which is a discipline surrounding effectively conveying messages and information in high-stress situations, where critical thinking and comprehension from the broader audience is less likely. Some examples of excellent risk communication occur in press conferences following disasters such as the September 11 attacks, or updates on epidemics and pandemics such as the Ebola and Covid-19 outbreaks. It acknowledges human nature and maintains diplomacy through easy-to-remember and procedural methods such that in a time of emotional volatility, effective communication is maintained [382].

10 Summary

Over the past two decades, and accelerating in recent years, wildland fire has increasingly posed a risk to communities around the world. This is perhaps most notable in North America and Australia, where warm and dry climates meet dense vegetation and urban infrastructure. The causes of which have been well analyzed and documented to be a conglomeration of effects from climate change, further overlap of the wildland-urban interface (WUI), and a collective lack of knowledge and action in fuels and forest management. As such, a call for change involves not only technological advancements, but also organizational and cultural adaptations to facilitate new ideas and modifications. This Concept of Operations (ConOps) looks forward with these causes in mind and proposes a future state of wildland fire operations in all the above to enhance mitigation efforts both in the Active Fire phase as well as the adjacent Pre- and Post-Fire phases. It organizes the wildland fire mitigation strategies discussed into seven sections within these three phases, to introduce changes in a chronological and logical manner. The seven links are thus referred to as the wildland fire "chain," consisting of 1) assessing previous year activity effectiveness, 2) assessing pre-year risk levels, 3) fuel reduction efforts, 4) ignition detection, 5) rapid initial attack, 6) extended attack, and 7) post-year recovery. In reality, these phases exist in a continuum and are cyclical by the seasonal nature of Earth's climate – to that end, changes are holistic and must evaluate the long-term impacts both positive and negative in the case that a novel feedback loop materializes. Therefore, when contriving new strategies, a prioritization methodology ranks their importance by balancing long-term with near-term benefits to gain initial momentum for these cumbersome institutional changes. Importantly, intermittent assessment of these changes is part of this concept, ensuring that resources are continually being put to effective use. Theoretical metrics for evaluating the impacts of this ConOps consist of statistical methods to evaluate multi-variable data. This data should be collected in the near term as a sample of control against which future efforts can be compared.

Wildland fire mitigation and response has always been a discipline driven by need. In recent years, that need has far outpaced the innovation and adoption of new strategies that address the increase in scope. However, with promising technologies and closer attention paid to the big picture of forest management, a path to a resilient wildland ecosystem is attainable through methodologies in this ConOps.

Abbreviations and Acronyms

3-DoF	Three Degrees of Freedom
6-DoF	Six Degrees of Freedom
AFUE	Aerial Firefighting Use and Effectiveness
AGL	Above Ground Level
AI	Artificial Intelligence
Alt	Altitude
AMD	Aeronautics Mission Directorate
ANCOVA	Analysis of Covariance
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
AO	Area of Operation
API	Application Programming Interface
App	Application
APU	Auxiliary Power Unit
AR	Augmented Reality
ARC	Ames Research Center
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATGS	Aerial Tactical Group Supervisor
ATV	All-Terrain Vehicle
AUS	Australia
BAER	Burned Area Emergency Response
BIA	Bureau of Indian Affairs
BIL	Bipartisan Infrastructure Law
BLM	Bureau of Land Management
BOR	Bureau of Reclamation
BVLOS	Beyond Visual Line of Sight
C&CAS	Coordination and Collision Avoidance System
C2	Command and Control (C&C) Data
CA	California
CalFire	California Department of Forestry and Fire Protection
CalTrans	California Department of Transportation
CDC	Centers for Disease Control and Prevention
CFD	Computational Fluid Dynamics
CFIT	Controlled Flight Into Terrain
CG	Center of Gravity
CMAT	Community Mitigation Assistance Team
CO	Carbon Monoxide
CO (State)	Colorado
CO2	Carbon Dioxide
Comms	Communications
ConOps	Concept of Operations
COP	Common Operating Picture
CRS	Congressional Research Service
CTOL	Conventional Take-Off and Landing
CWN	Call When Needed
CWPP	Community Wildland Protection Plan
DART	Dingell Act Resource Tracking
DC	District of Columbia
DFA	Distribution Fault Anticipation
DHS	Department of Homeland Security
DOA	Department of Agriculture
DOC	Department of Commerce
DOD	Department of Defense
DOI	Department of the Interior
DVE	Degraded Visual Environment
ECC	Emergency Command Center
EFD	Early Fault Detection
EMS	Emergency Medical Services
EO	Electro-Optical
EOS	Earth Observing Satellite
EPA	Environmental Protection Agency
EU	European Union
EWPP	Emergency Watershed Protection Program
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
Fig	Figure
FIRMS	Fire Information for Resource Management System
FRAMES	Fire Research and Management Exchange System
FSM	Forest Service Manual
FT	Feet
FTA	Fire Traffic Area
FWS	Fish and Wildlife Service
FY	Fiscal Year
GA	General Aviation
GACC	Geographic Area Coordination Center
GAO	Government Accountability Office
GLM	Geostationary Lightning Mapper
GNC	Guidance, Navigation, and Control
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System (Satellite)
GUI	Graphical User Interface
H2O	Water
HALE	High-Altitude, Long Endurance
HAM	Handheld Amateur (Radio)
Helo	Helicopter
HP	Horsepower
HR	Hour
H(V)TOL	Hybrid (Vertical) Take Off and Landing
Hyb	Hybrid
IA	Initial Attack
IAA	Initial Aerial Attack
IC	Incident Commander

ICS	Incident Command System
ID	Identification
IFPMS	Interagency Fire Program Management Standards
IFR	Instrument Flight Rules
IIJA	Infrastructure Investment and Jobs Act
IMET	Incident Meteorologist
IR	Infrared
IRA	Inflation Reduction Act
IS	Information Security
IT	Information Technology
ITC	Intertribal Timber Council
KIAS	Knots Indicated Airspeed
KTAS	Knots True Airspeed
LANCE	Land, Atmosphere Near-real-time Capability for Earth Observing Satellites
LDA	Linear Discriminant Analysis
Lidar	Light Detection and Ranging
LL	Lessons Learned
LMA	Lightning Mapping Array
LOS	Line of Sight
LRZ	Launch and Recovery Zone
Max	Maximum
MHz	Mega Hertz
Min	Minimum
ML	Machine Learning
Mob	Mobilization
MODIS	Moderate Resolution Imaging Spectroradiometer
MSL	Mean Sea Level
MVP	Minimally Viable Product
NARI	NASA Aeronautics Research Institute
NAS	National Airspace
NASA	National Aeronautics and Space Administration
NASF	National Association of State Foresters
NFDRS	National Fire Danger Rating System
NFIRS	National Fire Incident Reporting System
NIAC	National Interagency Aviation Committee
NICC	National Interagency Coordination Center
NIFC	National Interagency Fire Center
NIIRS	National Image Interpretability Rating Scales
NIST	National Institute of Standards and Technology
NM	Nautical Mile
NO	Nitric Oxide
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Airmen
NPS	National Park Service
NRR	National Ready Reserve
NSF	National Science Foundation
NVD	Night Vision Device
NWCG	National Wildfire Coordinating Group
NWS	National Weather Service
OAS	Office of Aviation Services
OIG	Office of the Inspector General
Op	Operation
OPM	Office of Personnel Management
OR	Oregon
Org	Organization
OWF	Office of Wildland Fire
PCAST	President's Council of Advisors on Science and Technology
PL	Preparedness Level
PM	Particulate Matter
PMS	Position Management System
PNAS	Proceedings of the National Academy of Sciences
PPE	Personal Protective Equipment
Prop	Propeller
PSA	Public Service Announcement
RAWS	Remote Automated Weather Stations
REMS	Rapid Extraction Module Support
RF	Radio Frequency
RID	Remote Identification
ROI	Return on Investment
RX	Prescribed
RXB	Prescribed Burn Boss
SAMSHA	Substance Abuse and Mental Health Services Administration
SAR	Search and Rescue
SATCOM	Satellite Communications
SMD	Science Mission Directorate
STEAC	Statewide Training and Education Advisory Committee
STMD	Space Technology Mission Directorate
STOL	Short Take Off and Landing
SWaP	Size, Weight, and Power
SWS	System-Wide Safety
TCAS	Traffic Collision Avoidance System
TFR	Temporary Flight Restriction
TO	Take Off
TRL	Technology Readiness Level
UAS	Uncrewed Aerial System
UAV	Uncrewed Aerial Vehicle
UC	University of California/Colorado
UHF	Ultra-High Frequency
UN	United Nations
UOM	Unit of Measurement
US	United States
USA	United States of America
USFS	United States Forest Service
USGS	United States Geological Survey
UTM	UAS Traffic Management
V&V	Verification and Validation
V2V2I	Vehicle-to-Vehicle-to-Infrastructure

VAMMS	Vehicle Add-on Mobile Monitoring System
VFR	Visual Flight Rules
VHF	Very High Frequency
VIIRS	Visible Infrared Imaging Radiometer Suite
VLAT	Very Large Air Tanker
VMC	Visual Meteorological Conditions
VOC	Volatile Organic Compound
VR	Virtual Reality
VTOL	Vertical Take Off and Landing
WA	Washington
WFAS	Wildland Fire Assessment System
WFIWG	Wildland Fire Industry Working Group
WFLC	Wildland Fire Leadership Council
WFPO	Watershed and Flood Prevention Operations
WIMS	Weather Information Management System
WTM	Wildfire Traffic Management
WUI	Wildland-Urban Interface
ZT	Zero Trust

Lexicon

For NWCG’s complete wildland fire glossary, please refer to PMS 205 [383].

Acre	n.	A unit of area in English units approximately equivalent to a 209 x 209-foot square.
Aft	adj.	In a ship, the relative location of a particular station as towards the rear or tail, as in "after."
Asset	n.	Equipment, such as planes, ships, communications, and radar installations, employed or targeted in tactical operations.
Azimuth	n.	In 3-D space, the name for the angle of rotation of the ground plane about the vertical axis, i.e., rotation about Z.
Bayesian	adj.	Relating to Baye's Theorem in statistics.
Beneficence	adj.	A concept of ethics as related to scientific studies where a researcher's ultimate motive of conducting the study is to improve the lives of, or benefit, the participants, thereby avoiding harm or otherwise inhumane treatment.
Big Data	n.	Colloquialism for very large sets of raw or unprocessed data that is collected often rapidly and non-discriminatorily.
Bleed (propulsion)	n.	Fluid that has been re-routed or diverted from one purpose to another, such as warm air in car engines to heat the interior cabin or air generated from an aircraft's auxiliary power unit to begin main engine startup (see: cranking).
Blivets	n.	Equipment worn on the back of firefighting personnel that contains a water tank and small hose used for localized fire suppression.
Boolean	n.	A binary variable, having two possible values called “true” and “false.”
Connectivity	adj.	Of or relating to the ability to transmit any type of data using any electromagnetic frequency. This can be as sophisticated in video uploading to the internet via satellite, or as simple as HAM radio.
Containment	adj.	In firefighting, the amount at which active flames are surrounded by suppression measures and other methods of impedance, given as a percentage of azimuthal coverage. This can be excavated fire lines, retardant drops, topological features such as cliffs and rivers, existing roads, etc.
Cordura	n.	A durable, synthetic fabric. Often nylon-based, found in military or other tactical environments.
Crank (propulsion)	v.	The physical act of turning the shaft of an engine to initiate startup, prior to fuel injection.
Digital Twin	n.	A fully simulated digital environment for situational testing and experimentation, aimed at achieving as much realism and fidelity as possible.
Downwash	n.	In moving fluids, pressure perturbations caused by upstream features seen by downstream features. Often when discussing the significant impact to aerodynamic performance such as a wing on horizontal tail stabilizers or aircraft wake turbulence.
Egress	v./n.	The act of departing, or the route taken while departing, a particular area.
Ember	n.	A small piece of carbon-based material that is burning slowly, such that no flames are present.
Extended Attack	n.	A designated phase in the wildland firefighting chain typically starting at least 48 hours after ignition, involving a large increase in personnel and a shift of suppression methodology from offensive to defensive due to increased fire spread.
Extractory	n.	A designated facility that cultivates fruiting plants in a controlled environment for the purpose of harvesting healthy seeds for further planting and rehabilitation efforts.
Fire Burn Boss	n.	In a prescribed burn, ensures that all prescribed fire plan specifications are met before, during, and after a high complexity prescribed fire. Implements the prescribed fire plan.
Firefighter	n.	Any personnel that assist onsite in the Active Fire phase.

Fuel	n.	In firefighting, any carbon-based material that is flammable and can contribute to the continuation of a combustion reaction and is not considered infrastructure.
Geo-Fence	n.	A digital boundary defined as part of a flight plan for a UAV, often denoted by coordinates or physical features in satellite imagery. This boundary triggers an override command in the aircraft autopilot to perform an avoidance maneuver or otherwise terminal descent such that the aircraft will not accidentally cross this line, which is particularly useful in areas near restricted airspace, property boundaries, or areas where the aircraft cannot otherwise be recovered.
Industry	n.	The combination of federal, state, and commercial entities within a discipline.
Informed Consent	n.	A concept of ethics as related to scientific studies where the participant is made fully aware of their right to voluntariness, as well as any procedure or environment they will be subjected to during the study to make an informed decision on voluntariness (see voluntariness).
Infrastructure	n.	Any human-made physical structure or hardware, often existing with legal documentation of existence or association to a documented owner. May or may not be flammable but distinguished as separate from fuel.
Ingress	v./n.	The act of entering, or the route taken while entering, a particular area.
Initial Attack	n.	A designated phase in the wildland firefighting chain consisting of the first 24-48 hours after ignition occurs involving first responders' ingress and assessment of the fire scope as well as suppression efforts.
Invasive	n.	In herbology, a plant or species of plant that is so well-adapted to a particular environment that it takes over the ecosystem and prevents other, necessary, species from contributing. Seen as a harmful.
LiDAR	n.	Light Detection and Ranging, a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the subject.
Logistics	n.	Referring generally to the various supporting and auxiliary operations in a tactical environment, such as transporting personnel, equipment, planning, process improvements, etc.
Megafire	n.	An uncontained wildland fire complex that has burned over 100,000 acres, typically with many smaller spot fires (See: Spot fire).
Mobilization	n.	The process and procedures used by all organizations, federal, state, and local, for activating, assembling, and transporting all resources that have been requested to respond to or support an incident.
Neural Network	n.	A digital method for data analysis that uses a set of rules, or algorithm, to combine and augment raw data into new variables, or features, which then can be used to update the parameters of the algorithm and converge on a result.
NextGen	adj.	Description of a product or form of technology that has been developed recently and is likely to replace current products or technology.
Null Hypothesis	n.	A statistical term describing the formal statement of an expected outcome in an event not occurring such that it can be tested as true or false.
Persistent	adj.	In technology, implying 24/7 usage, often with real time or near real time data sampling rates (see: real time).
Pitch	n.	In conventional flight dynamics, the rotation about the Y-axis, which moves the nose up and down, controlled by elevators located on the trailing edge of the horizontal stabilizers.
Portside	adj.	In a ship, the left side, or in the direction of the left side.
Prescribed Burn	n.	A fuels reduction strategy of using fire in a controlled way to intentionally burn away flammable material; sometimes called a controlled burn or RX Burn.
Real-Time	adj.	A sample rate of at least 20 Hz.

Redbook	n.	Annual document outlining the interagency standards for fire and fire aviation operations, as written by the DOI, NPS, USFWS BIA, and DOA.
Roadmap	n.	An outline or plan that breaks up a larger goal into smaller pieces with milestones, either time based or feature based.
Roll	n.	In conventional flight dynamics, the rotation about the X-axis, which leans the aircraft left and right, controlled by ailerons located at the outboard-most station on the wings.
Rotor Wash	n.	Downwash occurring from a helicopter rotor, often affecting the ground area during takeoff and landing; See "Downwash."
Second Shift	n.	Operations and activities that occur either in degraded visual environments (DVE) or after maximum time requirements are met for safety purposes, at which point current operations typically cease; formal description of night shift.
Silviculture	n.	The cultivation, control, and study of trees, specifically. Forestry.
Spinning/Spooling up/down	v.	Short-hand to describe the process of starting up an aircraft, which can be rather involved: starting with electrical power from either a generator or airport, aligning navigation systems, fueling the aircraft, starting an auxiliary power unit (APU), entering a flight plan, retrieving weather information, requesting ATC clearance, redirecting air from the APU to crank engine turbines (bleed), introducing fuel flow, setting takeoff performance parameters and lights, and performing the necessary briefings and checklists. Reverse for shutting down.
Spot Fire	n.	A secondary fire ignited by aerial embers or debris from an originating fire, often separated by unburned area.
Starboard	adj.	In a ship, the right side, or in the direction of the right side.
Tabletop	n.	A discussion-based session where team members meet in an informal, classroom setting to discuss their roles and responses to a particular situation.
Topography	n.	The physical and quantitative attributes of the ground, such as bi-directional slope, elevation, composition, as well as description of features such as boulders, cliffs, streams, etc.
Trim	n.	In aircraft, a small control surface secondary to the primary control surface which can be manually moved and set by the pilot to counteract bias or drift in that axis, which reduces the magnitude of input commands required by the pilot.
Uncrewed	adj.	A vehicle in which no human is onboard, be it fully autonomous or remotely piloted.
Visionary	adj.	A description of an era of time 11-15 years in the future, from a technical maturation standpoint.
Voluntariness	adj.	A concept of ethics as related to scientific studies where the participant is not coerced into participation, nor to provide any specific answer. Likewise, they are allowed to rescind their participation at any time before, during, or after a study has been conducted.
White Paper	n.	A formally published and peer reviewed piece of technical writing.
Wildland	n.	An area in which development is essentially non-existent, except for roads, railroads, powerlines, and similar transportation facilities. Structures, if any, are widely scattered.
Yaw	n.	In conventional flight dynamics, the rotation about the Z-axis, which moves the nose left and right, controlled by the rudder located at the trailing edge of the vertical stabilizer.

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