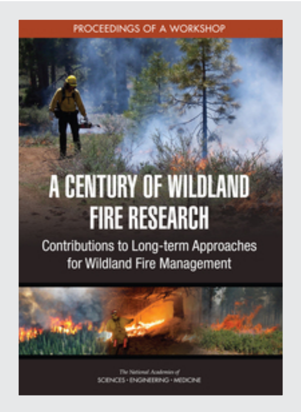

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A CENTURY OF WILDLAND FIRE RESEARCH

Contributions to Long-term Approaches for Wildland Fire Management

PROCEEDINGS OF A WORKSHOP

Kara N. Laney, *Rapporteur*

Committee on Increasing Resilience to Wildland Fire:
A Century of Wildland Fire Research

Board on Earth Sciences and Resources

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

The National Academies of
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1

Introduction

Although ecosystems, humans, and fire have coexisted for millennia, changes in geology, ecology, hydrology, and climate as well as sociocultural, regulatory, and economic factors have converged to make wildland fire management exceptionally challenging for U.S. federal, state, and local authorities. Increasingly dry conditions, stresses on native flora and fauna (including those imposed by invasive species), and landscapes that have been altered both by humans and previous wildland fires all shape the management options available today when it comes to wildland fire (Coughlan and Petty, 2012; Flannigan et al., 2013). Such changes can result in compounding ecological effects such as erosion and landslides, new river and stream patterns, and different composition and functioning of ecosystems (for example, Miller et al., 2013; Riley et al., 2013). Changes to human settlement patterns, particularly the trend to build and occupy permanent structures along the edge of wildland (that is, within the wildland–urban interface), similarly affect management options (Mercer and Zipperer, 2012). The confluence of factors also affects and often limits the approaches available for living with wildland fire.

Wildland fire includes both prescribed fire (fire that is deliberately ignited to meet specific objectives) and wildfire (unplanned fire in wildland). In 2014, over 4.7 million hectares (12 million acres) in the United States were treated with prescribed fire (Melvin, 2016). That same year, 1.5 million hectares (3.6 million acres) of wildland burned due to wildfire (NICC, 2014). In the following year, that area nearly tripled to 4.1 million hectares (10.1 million acres) (NICC, 2015). The amount of area burned by wildfire has been increasing steadily in the United States over the last 3 decades (Figure 1-1), as have the costs to federal agencies of suppressing wildfires (Figure 1-2). These rising suppression costs consume more of the agencies' budgets and frequently cause funding for preemptive fire and forest management activities, such as prescribed burning and forest thinning, to be diverted to emergency firefighting efforts (WFLC, 2010).

However, suppression costs do not capture the full cost of fire. Even with the resources devoted to suppressing wildfire, destruction and damage occur, often with extremely tragic outcomes. For example, in the 2016 fire season the Great Smoky Mountains wildfires near

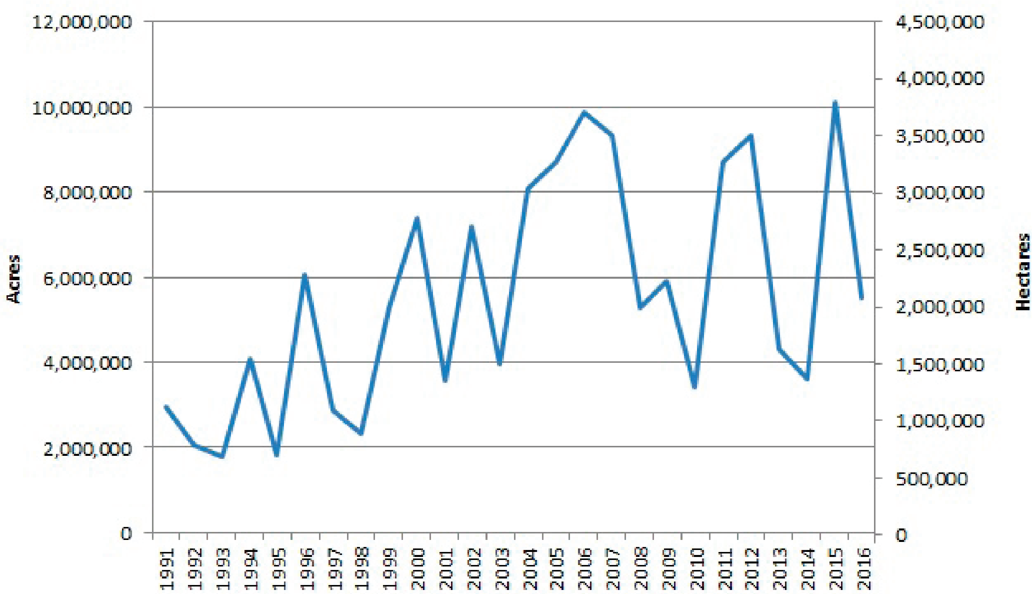

FIGURE 1-1 Annual area burned by wildfire in the United States, 1991–2016.
NOTE: Data include Alaska and Hawaii.
DATA SOURCES: NICC, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016.

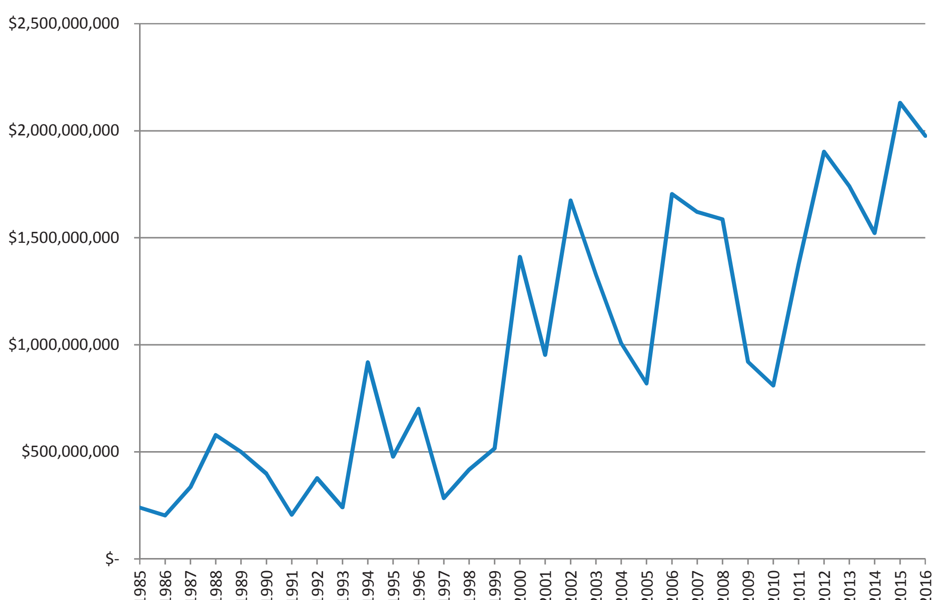

FIGURE 1-2 Federal firefighting costs (suppression only) in U.S. dollars, 1985–2016.
NOTE: Costs are not adjusted for inflation.
DATA SOURCE: Federal Firefighting Costs (Suppression Only), available at https://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf. Accessed June 18, 2017.

Gatlinburg, Tennessee, killed 14 people, injured 130, and forced 14,000 to evacuate the area. More than 1,600 structures were damaged or destroyed by this one fire complex (Gabbert, 2016). Costs related to rehabilitating a burned area (including short-term clean-up efforts and long-term environmental restoration), lost tax and business revenue and property value following a wildfire, health effects from smoke exposure, emergency evacuations, and loss of life can swamp the expense of fighting fires, sometimes reaching 30 times the amount spent on a fire's suppression (WFLC, 2010).

The increasing proportion of federal, state, and local budgets directed to fire suppression reduces the capacity of those agencies responsible for managing wildlands to develop and implement long-term strategies that account for the full wildland fire cycle of mitigation, preparedness, response, and recovery. With extensive wildland–urban interfaces, the United States is particularly exposed to the financial risks of managing wildland fire relative to the rest of the world.

Although federal agencies—and their state and local counterparts—make significant efforts to coordinate their activities, leverage resources, and define future priorities through interagency mechanisms such as the Joint Fire Science Program, the National Cohesive Strategy for Wildland Fire Management, and the National Interagency Fire Center, these institutions nonetheless struggle to collectively address managing fires in wildland areas and to develop strategies for making landscapes resilient to wildland fire over the long term. There is general agreement that high quality wildland fire science is available but that translating this science into actionable policy initiatives is difficult.

Therefore, given the mounting, unsustainable costs and difficulty translating existing wildland fire science into policy, the National Academies of Sciences, Engineering, and Medicine organized a 1-day workshop to focus on how a century of wildland fire research can contribute to improving wildland fire management. The workshop was organized at the behest of the U.S. Forest Service.

OVERVIEW OF THE WORKSHOP

The workshop was organized and convened by a planning committee and held on March 27, 2017, at the National Academy of Sciences in Washington, DC (see agenda in Appendix A). The planning committee (see biographies in Appendix B) developed the agenda around a statement of task (Box 1-1) established by the National Academies and the U.S. Forest Service. Participants were drawn from the Forest Service, the U.S. Department of the Interior, other federal agencies, nongovernmental conservation organizations, universities, and emergency management organizations. More than 100 people attended the workshop, and an additional 200 participated remotely via webcast.

The workshop began with a welcome from Dr. Gregory Symmes, executive director of the National Academies' Division on Earth and Life Studies, and presentations on the legacy of fire science research in the U.S. Forest Service. Keynote speakers and panelists then spoke about the following concepts:

- Learning from more than 100 years of fire science research
- Anticipating future fire regimes
- Understanding the current state of fire science research
- Understanding the complexities of living with wildland fire

Following presentations on the above concepts, some workshop participants broke into multidisciplinary working groups to explore pinpointing research priorities for different U.S.

BOX 1-1
Statement of Task

An ad hoc planning committee appointed by the National Academies of Sciences, Engineering, and Medicine will organize a workshop to examine the last century of wildland fire research in context of

(1) recent, rapid increases in extreme fire behavior and the hazards and risks these fires pose to communities and landscapes; and
(2) the occurrence of wildfire as an integral part of the natural, healthy evolution of landscapes.

Specific attention will be given to scientific results, capabilities, and information that have been or can aid wildland fire managers, policymakers, and communities in support of a more strategic, long-term approach to wildland fire management.

Specifically, the workshop will feature invited presentations, discussions, and breakout activities that will address the research status, needs, and challenges related to

(1) Helping wildland fire managers and responders discriminate between “good” and “bad” fires;
(2) Adaptive fire and forest management;
(3) Proactive approaches to landscape level fuel management; and
(4) Societal needs and considerations to support and implement long-term wildland fire management strategies.

regions, using technology in wildland fire management, integrating science into management actions, and engaging stakeholders.

ORGANIZATION OF THE PROCEEDINGS

This proceedings of a workshop summarizes presentations and discussions on ways in which science can help wildland fire planning and management be more strategic, reduce costs, and ultimately increase resilience to wildland fire, both on the land and in communities affected by fire. Its organization follows the structure of the workshop. Chapter 2 summarizes remarks given by representatives of the U.S. Forest Service. Chapter 3 captures the presentations of the workshop’s two keynote speakers, who focused on the United States’ past and future with fire, respectively. Chapters 4 and 5 review the current understandings of the state of the science relative to fire and the challenges to living with fire. Biographies for all the workshop speakers can be found in Appendix C. Chapter 6 summarizes the results of the afternoon’s discussions in the breakout sessions.

This proceedings of a workshop has been prepared by the rapporteur as a factual summary of what occurred at the workshop. The planning committee’s role was limited to planning and convening the workshop. The views contained in the proceedings are those of individual workshop participants and do not necessarily represent the views of all workshop participants, the planning committee, or the National Academies of Sciences, Engineering, and Medicine.

2

Fire Science Research in the U.S. Forest Service

Dar Roberts, chair of the workshop planning committee, extended his welcome to the invited speakers, audience members in attendance, and those watching on the webcast. He introduced the three speakers from the U.S. Forest Service, who provided their own words of welcome and reviewed the history of fire science research in that federal agency.

RESEARCH IN THE U.S. FOREST SERVICE

Carlos Rodriguez-Franco, U.S. Forest Service

Rodriguez-Franco began by noting that the workshop was an opportunity to celebrate 100 years of research and development in the U.S. Forest Service. In the 1870s, the changing nature of society's interaction with forests and natural resources created the need for a federal research organization. In 1872, Congress asked the U.S. Department of Agriculture to prepare a report on the conditions of American forests. However, it was not until 1898 that forest research began under Gifford Pinchot, when he was named the chief of the Division of Forestry. When the division was renamed the Forest Service in 1905 and given the mission of managing the forest reserves, headwaters, lands reserved for the public, and land to protect watershed and forest resources, it needed immediate scientific information. To gather this information, Pinchot established a section of special investigations. The importance of research to forest management was formalized in 1915 with the creation of a branch of research in the Forest Service.

To accomplish and support the mission of the Forest Service, the Research and Development Unit has carried out basic and applied research to establish the foundation of contemporary forest management. Its broad program areas are landscape restoration and ecosystem services, sustainable forest management, science policy, planning and inventory, and forest product research. Rodriguez-Franco drew specific attention to one more program area: wildland fire research, the focus of the workshop. Nearly 500 scientists work for the Research and Development Unit, along with numerous technicians and support personnel, and there are programs in every U.S. state and territory. Forest Service Research and Development findings are used by scientists and practitioners in the United States and in many countries around the world, including those at nongovernmental organizations, environmental groups, and universities.

Rodriguez-Franco noted that the Research and Development Unit's niche is providing forest management and use applications and long-term research and analysis of trends over temporal and spatial scales. That long-term research facilitates the monitoring of natural resources on different temporal scales as well as the integration of studies from local to transcontinental levels in the United States. The Forest Service's network of experimental forests and ranges are the backbone of its long-term studies because 100 years of data have been collected in these locations. Almost all the experimental forests are located in national forests, and they represent a broad range of environmental landscapes and conditions. Its national Forest Inventory and Analysis Program has tracked the status changes on public and private lands for more than 80 years. The Research and Development Unit conducts research on federal, state, and private lands in partnerships with other government agencies, universities and other research institutions, industry, and local government organizations and has produced more than 45,000 publications.

The work of the Forest Service Research and Development Unit sustains America's forests and improves lives and American society by benefiting the environment, creating jobs, supporting local economies, and saving lives, particularly when wildland fires occur because of adverse environmental conditions. However, at the turn of the 21st century, new interactions and social forces are shaping the need for a new strategic direction for research and development within the Forest Service. Rodriguez-Franco said that is was for this reason the Forest Service supported the workshop to help shape future decades of forest research and development related to wildland fire. He concluded his comments by drawing attention to two recent publications by the Research and Development Unit related to the workshop's topic: *Sustainability and Wildland Fire: The Origins of Forest Service Wildland Fire Research* (Smith, 2017) and *Research and Development Wildland Fire and Fuels: Accomplishments and Outcomes* (Rollins et al., 2017).

A HUNDRED YEARS OF FIRE SCIENCE AND MANAGEMENT AT THE FOREST SERVICE

Thomas L. Tidwell, U.S. Forest Service

Chief Tidwell observed that much had been learned about the science of fire over the last 100 years but acknowledged that the Forest Service was still trying to find solutions with regard to addressing wildland fire in the United States. The Forest Service suppresses about 98 percent of all wildland fires on National Forest System lands, but the 2 percent of the fires that escape initial attack quickly become very large. Tidwell noted that the rate at which those fires grow has increased during his 40-year career with the Forest Service. Current environmental and climatic conditions are causing those fires to become larger and hotter more quickly and expand beyond the wildland fires of the past. Those changes in wildland fire have implications for firefighter safety. Society needs the Forest Service to be able to suppress wildland fire, but the result is often that firefighters lose their lives on the fire line.

Tidwell commented that many people think the Forest Service has its origins in the Big Burn in 1910 (Box 2-1). According to Tidwell, prior to the 1910 burn, Chief Gifford Pinchot probably thought fire was just a nuisance; he likely did not understand the complexities of the situation. When the Big Burn began, Pinchot was no longer at the helm of the Forest

BOX 2-1
The Big Burn

The Big Burn of 1910—also known as the Great Fire of 1910, the Big Blowup, and the Devil's Broom Fire—was a wildfire in the northwest United States that burned over 2 days in August. The Big Burn was the Forest Service's first large fire fight since the agency's establishment in 1905, and it was a formative and traumatizing experience. More than 9,000 firefighters were on the payroll by the time the crisis ended; 78 firefighters lost their lives in the fire, which burned 1.32 million hectares (3.25 million acres) in northeastern Washington, northern Idaho, and western Montana (Pyne, 2010).

Service, and following that fire, it became clear that not only was there a need to manage the national forests but also that one of the highest priorities for every ranger in the Forest Service was to protect forests from fire.

William Greeley, the third Forest Service chief, questioned and criticized the concept of light burning, also referred to as Piute Forestry. Light burning was the way that Native Americans in North America used fire for various purposes—from creating a habitat to being able to provide for their livelihood. However, this approach was in direct contrast to the European mindset toward fire, which emphasized the need to put out fire. The controversy of whether to use a light-burning approach—that is, to set fires purposefully to achieve habitat or livelihood objectives—continued for many years in the United States. It was not until the 1960s that the Forest Service started to apply some of the knowledge and the science regarding the need for fire in the ecosystem. The Forest Service started using this concept with fire in back-country wilderness areas.

In 1978, the Forest Service developed the concept of appropriate suppression action. With this step, the Forest Service acknowledged for the first time that not all fire was bad and put in place policies to that end. Prescribed fire was used in some places, and the Forest Service recognized the need to better understand the benefits of lightning-ignited fire. It sought to take action to suppress lightning-ignited fires or suppress the parts of the fire where appropriate, while also understanding the need for fire to play a role in ecosystems. However, implementation of this policy was challenging and the use of fire in the landscape was not common at that time.

The Forest Service continued to use science and knowledge to inform and shift its policies. Around 2009, it developed the policy that there are two types of fire: (1) planned fire, that is, prescribed fire ignited by the Forest Service, and (2) unplanned fire. With unplanned fire, there is the opportunity to take appropriate suppression actions to manage fire in a way that allows direct suppression action on part of the fire if needed and at the same time to recognize that there may be a need to let fire burn to accomplish some resource benefits. Unplanned fires can be managed with multiple approaches when it comes to suppression.

Recently, the Forest Service has followed the direction from Congress to develop, in conjunction with the U.S. Department of the Interior, the National Cohesive Wildland Fire Management Strategy. The cohesive strategy reached out to everyone that interacts with wildland fire policy and management—local communities, counties, cities, and states. The strategy has three elements. The first is to restore fire to the landscape using both prescribed fire and wildfire to create healthy, resilient, fire-adapted ecosystems. The second is to help communities adapt to living with fire by adopting fire-wise practices, that is, to make their communities safe from the fire and to create defensible space so that wildland firefighters have a place to work and safely suppress fire. The third is to make appropriate risk-based decisions when it comes to managing every wildland fire.

The Forest Service has made strides with the strategy. Tidwell said he believes that today there is more recognition of the need for fire in the ecosystem. More has been learned about the benefits of fire-wise techniques and technologies, and there is now the science available to show homeowners the difference that can be made in terms of safety to their homes if they take some simple steps to clear brush and remove firewood stacks around the house. These strides are making a difference.

However, even with these advances, the Forest Service is struggling to get more fire on the landscape—that is, to have more land burned each year, either through lightning-ignited fires or prescribed fires, in a way that is acceptable to local communities, that accounts for human safety, and that helps preserve the function of ecosystems that have evolved with fire. In fact, a study conducted by the National Interagency Fire Center in Boise from 1998 to 2008 looked at the ratio of wildfires that were suppressed to those in which wildfire was used for resource benefits. The study found that the ratio of wildfires that were suppressed to those in which wildfire was used for resource benefits was 249 to 1. Good results have been seen from this work, but it is a small accomplishment when compared to the number of wildfires that could be managed to such ends and are instead suppressed.

Tidwell gave the following challenges to the workshop audience: How can more fires be allowed to burn, whether they are set by lightning or people? How can fire burn in all types of landscapes, not just in the wilderness areas or in the back country? How do people learn to live with smoke? When it comes to the thinning of forests to reduce biomass, if mechanical removal is not followed with prescribed fire, the effectiveness of those treatments drops significantly. Therefore, even with mechanical treatment on the landscape, there is still a need for prescribed fire or wildfire managed for resource benefits. Tidwell asked the audience to think about how the existing science could be better used to effectively inform decision making so that communities, incident commanders, line officers, and elected officials can understand when there is an opportunity to take the appropriate suppression response—to suppress the part of the fire that is causing concern, safety issues, and threats to the communities—and at the same time recognize the benefits of fire and its effects on the landscape.

Tidwell acknowledged other challenges facing the Forest Service. Fire knows no boundaries. The 7,000 wildfires that burn on Forest Service land each year are just 10 percent of the wildland fires that occur every year in the United States. Therefore, wildland fire is not just a federal agency issue. Making a change with how fires are managed will require cooperation and action beyond just the Forest Service. Additionally, the 44 million homes located in the wildland–urban interface today complicate the Forest Service's work. More houses will be built in these locations in the future. While it is understandable that people want to live in those interface environments, those homes reduce the number of fire-management options available because of the need to keep fire away from communities and homes. The Forest Service also continues to strive toward the concept of life first when it comes to dealing with suppression of wildland fire to ensure that every land and aerial firefighter comes home safely at the end of the day.

Since its establishment, the Forest Service has learned to advance and revise its policies and to apply science to manage the landscape to make a real difference. Tidwell challenged the audience with the following questions: What science is missing that the Forest Service and others in the field need to work together and develop? What science, tools, and techniques are not being applied, or how can science be better applied to the landscape? What needs to happen for the United States to acknowledge and face the challenges of wildland fire? What additional science is needed and what more is there to learn in order for the Forest Service to move forward in a way that ensures there is more fire on the landscape?

Tidwell concluded by acknowledging there is no question that fire is needed to preserve the function of ecosystems that have evolved with fire. Wildland fires will continue to occur. The best option is to affect how and when wildland fire occurs. As a nation, everyone has to come to an understanding that there is a need for more wildland fire on the landscape.

SUSTAINABILITY AND WILDLAND FIRE: THE ORIGINS OF FOREST SERVICE WILDLAND FIRE RESEARCH

Diane M. Smith, U.S. Forest Service

Smith presented material from her recent book, *Sustainability and Wildland Fire: The Origins of Forest Service Wildland Fire Research* (2017), and focused on the early years of the fire research in the Forest Service. Her book has three main themes. The first is sustainability, that is, how to sustain the national forest. The second is forestry versus fire. The newly trained foresters at the beginning of the 20th century could not practice the science of forestry without first learning how to control fire. The third theme is public education. History shows that education is important not only for the general public but also in the Forest Service's efforts to engage with homeowners and even with U.S. forest rangers responsible for handling fire in the field.

The research arm of the Forest Service was officially established in 1915 with the objective to bring a unity of purpose to the research within the Forest Service, not just fire science but all research. Gifford Pinchot's goal for the Forest Service and its research on fire was to replace vague general notions about fire with carefully gathered facts. However, the importance of research begins even earlier in the history of the Forest Service. In 1873, Franklin B. Hough presented a paper about the importance of protecting the nation's forests; 3 years later, Congress appropriated $2,000 for a new office of the Agent of Forestry. Hough was hired to be the agent; he was not hired to manage lands but to research or investigate the condition of the nation's forests and report back to Congress. He created three large volumes of the conditions and data of forests, including fire. Therefore, when Smith is told that the Forest Service is a management agency, she likes to counter that it was in fact formed on a foundation of research.

One of the interesting things from the very first Forest Service annual report by Gifford Pinchot in 1898 is how little was known about forest fires and how essential that was to the practice of forestry (Pinchot, 1898:172). Finding ways to control wildland fire became an early focus, and that same year, Pinchot established an Office of Investigations for research in general, including fire. The creation of this office established the Forest Service as an agency that conducts research.

After the creation of the office, Pinchot initiated several research efforts. He organized collaborative investigations of fire in the West and in the Northeast. He started a study of forest fires, directing some of his researchers go through all the major U.S. newspapers and find every mention of forest fires in U.S. history. This effort resulted in the cataloging of 10,000 fires by 1901. He also sent individual investigators out into the field to report back fire conditions. These reports were extensive overviews of the effects of fire on communities and economies. It is apparent from his writings that Pinchot took fire research very seriously. A 1904 memorandum found in the National Archives, probably written by Pinchot himself although there is no attribution or specific date, confirms the timeline of the beginning of fire science research in the Forest Service (Figure 2-1). A U.S. Department of Agriculture letter from 1905, likely written by Pinchot but signed by the secretary of agriculture, contains an early vision of the Forest Service's mission statement (Wilson, 1905):

> In the administration of the forest reserves it must be clearly borne in mind that all land is to be devoted to its most productive use for the permanent good of the whole people, and not for the temporary benefit of individuals or companies.

However, in 1910, Pinchot was fired by the Taft administration for protesting decisions made in opposition to that mission statement. Henry Graves succeeded Pinchot and in the same year published *Protection of Forests from Fire*, in which he said "the first measure necessary for the successful practice of forestry is protection from forest fires" (Graves, 1910:7). Shortly after the report was published, the Big Burn of 1910 began.

Early research in the Forest Service was generated in places other than Washington, DC. People around the country were doing relevant work in fire research, particularly Coert DuBois in California. DuBois sent a letter to all California district rangers urging them to reduce fire protection to a science. He wanted to identify what was known, so that research efforts could then be focused on what was not known. He rightly foresaw that those who contributed to this research would be known thereafter in the field of forestry.

Indeed, several people became famous for their fire research endeavors. Julius Larsen conducted some of the early fire work in the Priest River experimental forest in northern Idaho. Harry Gisborne was the first full-time Forest Service fire researcher and a leader in establishing fire-danger rating. Jack Barrows was hired by Gisborne to conduct a number of projects and was instrumental in establishing the Missoula Fire Sciences Laboratory and securing federal funding for additional regional laboratories in California and Georgia.

There were also infamous researchers in the early days of the Forest Service. S. B. Show was bitterly opposed to light burning. He conducted a series of light-burning projects and, to make sure that his research did not in any way support fire on the landscape, he worked with his colleague E. I. Kotok to undermine the results significantly (Smith, 2017).

Even though research had been under way for many years and the Bureau of Forestry had officially become the U.S. Forest Service in 1905, there was still no official research branch within the agency. In 1912, Graves established a central committee on investigative work to advise him on research, and the following year he created a new Office of Forest Investigations, trying to improve how research in the Forest Service was done. Ultimately in June of 1915, he consolidated all research in a new Branch of Research to protect researchers from day-to-day management and to give them the fullest possible recognition. One reason

"The study of forest fires was begun by this Bureau in 1899 and was mainly confined to studies made in connection with other work and to a compilation of historical data until 1902. It was reorganized in that year and begun upon a basis of independent field studies."

-- Forest Fires, ca. 1904

Oregon fire, 1904

FIGURE 2-1 Quotation on the origins of research in the U.S. Forest Service from 1904 memorandum on forest fires.
SOURCE: Smith, slide 7; photo courtesy of the Forest History Society, Durham, NC.

that Graves likely may have felt strongly about establishing this branch was that employees who were poor administrators were being put on research projects. The reputation of their work so discredited the field of research within the Forest Service that prospective employees did not want to pursue research. Thus, the new Branch of Research was a way for Graves to elevate the profession of research.

The year after the research branch was established the Forest Service put together a ledger book of all the various research projects that were under way. One was a 1-year project to determine a better way to distribute firefighting funds based on risk. The branch also conducted three long-term, open-ended projects: (1) the study of the relationship between weather conditions, fire hazard, and protection (in other words, fire-danger rating), (2) an investigation of better methods of fire prevention, detection, and control, and (3) the development of uniform principles for estimating the effects of fire, particularly the negative effects and the cost.

Smith closed with quotes from Pinchot (Figures 2-2 and 2-3) and with a request that researchers document their work for historians to piece together. Today's paper trail will help tell the story of forest and fire science research 100 years from now.

Forest Service Research

- "The object of forestry is to discover and apply the principles according to which forests are best managed." (1903)
- The goal of fire research was to replace "vague general notions" with "carefully gathered facts." (1903)
- "The documents upon the subject still reside, with very few exceptions, in the forest itself." (1899)

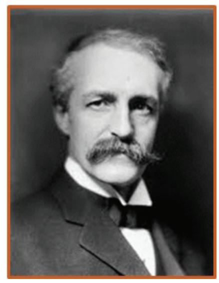

FIGURE 2-2 Quotes by Gifford Pinchot on forest and fire science research.
SOURCE: Smith, slide 16; photo by Pirie MacDonald, courtesy of the Library of Congress.

"The central thing for which Conservation stands is to make this country the best possible place to live in, both for us and our descendants.

It stands against the waste of the natural resources which cannot be renewed, such as coal and iron; it stands for the perpetuation of the resources which can be renewed, such as the food-producing soils and the forests; and most of all it stands for an equal opportunity for every American citizen to get his fair share of benefit from these resources, both now and hereafter."

Gifford Pinchot, 1910

FIGURE 2-3 Quote by Gifford Pinchot from his book *The Fight for Conservation*.
SOURCE: Smith, slide 17; Pinchot (1910:79).

3

The Past and Future of Fire in the United States

The workshop's two keynote speakers reviewed what fire science in the United States has accomplished in the last 100 years and what the results of that research reveal for the next 100 years. Dr. Stephen Pyne, a historian at Arizona State University, presented on the U.S. history of fire science research. He was followed by Dr. Jennifer Balch, director of Earth Lab at the University of Colorado, Boulder. Each answered questions from the audience following the presentation.

FIRE SCIENCE'S AMERICAN CENTURY

Stephen J. Pyne, Arizona State University

Pyne began by saying he appreciated the fact that the Forest Service considers history as part of its mission. Many fire problems are, in some ways, historically constructed, so understanding how that evolution has occurred is crucial to understanding how to respond to fire today. The history of wildland fire research is the story of ideas (many of them very old) and of institutions (most of them quite young) and how the two have come together.

Pyne gave a brief prologue about the turning point in the history of fire science before examining that history with specific regard to the United States. He said that turning point was when the earth's keystone species for fire—humans—shifted its combustion habits from burning living biomass and surface fuels to burning fossil biomass. He labeled this shift a "pyric transition," a move from open fire in landscapes and domiciles to one of fire in combustion chambers. The shift to industrial burning also had an intellectual component because fire ceased to have autonomy as a field of science. Unlike the other elements—air, water, and earth—fire would henceforth be studied as a subset of other forms of learning. Fire as a science in its own right would be suppressed just as open flames were suppressed following the shift to industrial burning.

The United States' fire-science story began in earnest in the late 1800s, coincident with the Industrial Revolution. Up to that point in time, fire was a common occurrence on the land. It was used by Native Americans and later by settlers for many purposes, including clearing land and preparing fields. Indeed, slashing and burning on an industrial scale was common in other colonized places, such as Australia, Canada, and Russia (Pyne, 2010). The United States, like its colonizing peers with large tracts of forested land, responded to rampant slashing and burning with state-sponsored conservation, which set aside and put under national control large tracts of land that had once been inhabited by indigenous peoples (Pyne, 2010). These tracts then needed to be surveyed. A survey of western lands conducted by John Wesley Powell in the 1870s, resulted in, among other things, the first map of fires (Figure 3-1). Powell's map was included with other material gathered by Charles Sargent for the 1880 U.S. Census report on forests (Sargent, 1884) to create a map of forest fires in the United States (Figure 3-2). Sargent, who was the director of the Arnold Arboretum at Harvard University, went on to be instrumental in rallying the National Academy of Sciences to sponsor the National Forest Commission (Box 3-1), which investigated how to manage the new forest reserves preserved by the federal government.

The linkage between forestry and fire management made in the National Forest Commission's statement of task persisted in the commission's recommendations; the connection between the two was then translated from those recommendations into federal legislation and into the mission of the newly formed Forest Service in 1905. Forestry as a discipline in the United States thus inherited the task of managing fire in the forest reserves, which of course required information on which to base that management. However, forestry was a young discipline in the United States, and it had no academic heritage of fire or fire management. Early U.S. foresters such as Pinchot were trained in Europe, where fire was seen as preeminently a social problem and was stigmatized as primitive (Pyne, 2010). A person's or a society's use of fire signaled whether the person or society was rational or primitive, and this point of view was exacerbated by the politics of the time, which were preoccupied with expansion and imperialism. Bernard Fernow, the first U.S. professional forester (originally from Prussia), equated the use of fire by Native Americans and settlers with bad habits and loose morals. He declared, as did others, that fire protection was not properly a part of forestry; rather, fire protection needed to be in place before forestry could be conducted.

The result was that the Americans who inherited the task of understanding landscape fire dismissed fire as a legitimate part of an ecosystem and wanted to remove it from the landscape. Like Fernow, Gifford Pinchot saw the removal of fire from forests as a necessary precondition to managing the forest reserves. This view became embedded in the Forest Service and was solidified by the Big Burn of 1910 (see Box 2-1), which challenged the ability of the agency to fight fires. The light-burning controversy, which also flared up in August 1910, challenged the Forest Service's authority to make policy, while the Weeks Act, passed by Congress in 1911, created the circumstances for the formation of a truly national forest system (Box 3-2). Thus, for Henry Graves—who succeeded Pinchot as Forest Service Chief in 1910—protecting forests from fire was, as he said, 90 percent of American forestry. William Greeley, who would succeed Graves as chief in 1920, said in 1911 that firefighting was a matter of scientific management, in principle no different than silviculture or other techniques. Two decades later, Earle Clapp, associate chief and acting chief in the late 1930s, agreed, arguing that forest fire research was the United States' responsibility because there was no precedent in Europe. In part to address this need for forest fire research, a branch of research was established within the Forest Service in 1915. Experimental forests, including those for fire, were in place by 1916.

However, the real motivator for fire science in the Forest Service was Coert DuBois, a forester in California. In 1914, he published the results of his study, *Systematic Fire Protection in the California Forests* (Dubois, 1914). He used operations engineering of his day,

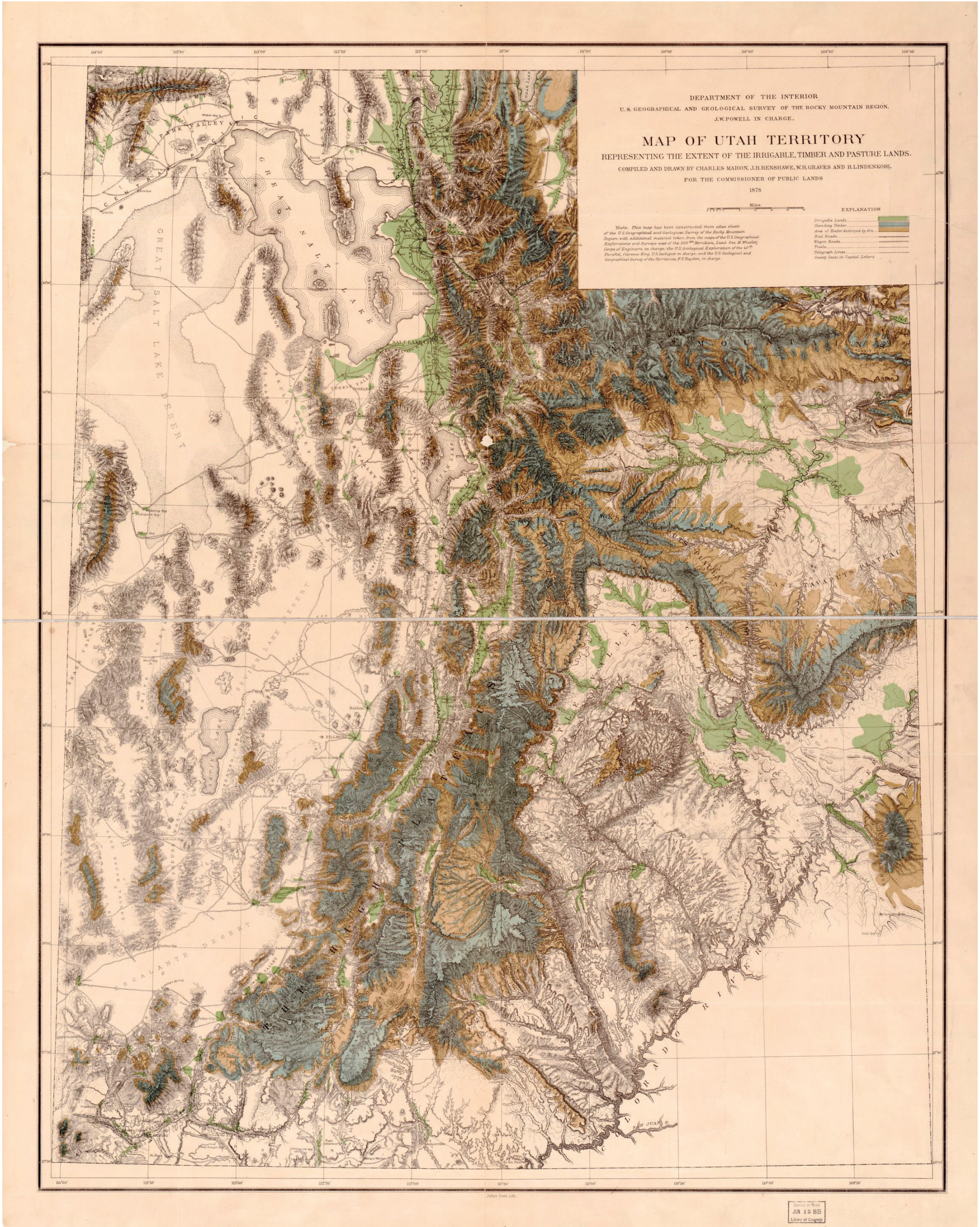

FIGURE 3-1 Map of Utah territory representing the extent of the irrigable, timber, and pasture lands.
NOTE: Tan area represents burned forest land.
SOURCE: Pyne, slide 4; Mahon et al. (1878).

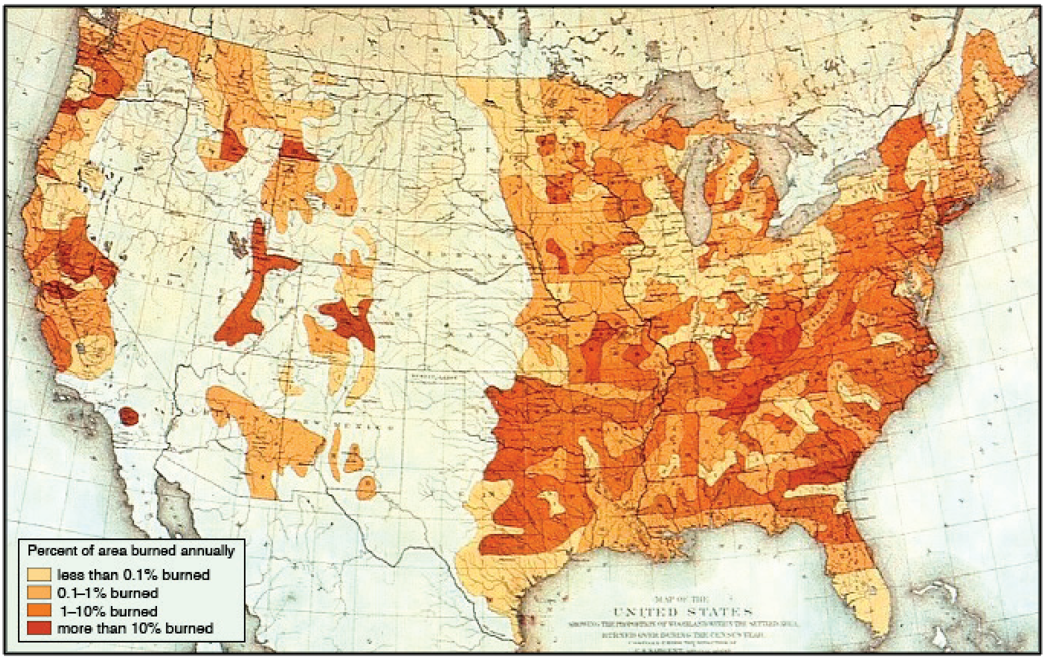

FIGURE 3-2 Map depicting the proportion of woodland burned in the conterminous United States in 1880.
SOURCE: Pyne, slide 4; Sargent (1884).

BOX 3-1
The National Forest Commission

In 1896, the Secretary of the Interior, Hoke Smith, asked the National Academy of Sciences to convene a group of forestry experts to answer the following questions:

1. Is it desirable and practicable to preserve from fire and to maintain permanently as forest lands those portions of the public domain now bearing wood growth for the supply of timber?
2. How far does the influence of forest upon climate, soil, and water conditions make desirable a policy of forest conservation in regions where the public domain is principally situated?
3. What specific legislation should be enacted to remedy the evils now confessedly existing?

Charles Sargent chaired the committee. Its members included General Henry L. Abbot, retired from the U.S. Army Corps of Engineers who had conducted surveys for the U.S. Pacific Railroad in the West in the 1850s; Alexander Agassiz, a curator at the Harvard Museum of Comparative Zoology; William H. Brewer, the state botanist for California; Arnold Hague, a geologist with the U.S. Geological Survey; and Gifford Pinchot, who was the secretary of the commission. Wolcott Gibbs, as the president of the National Academy of Sciences, served as an ex-officio member of the commission. The commission conducted its work in 1896 and 1897 and produced reports and recommendations that influenced future legislation related to the management of public forests.

SOURCE: Williams and Miller (2005).

BOX 3-2
The Weeks Act

The Weeks Act of 1911 authorized the purchase of private land by the federal government to protect watersheds; it thereby allowed for the expansion of the national forest system. It also established a program of federal and state cooperation for controlling fire. The legislation was particularly crucial to establishing national forests in the eastern United States. Over the next 50 years, over 8 million hectares (20 million acres) of forested land would come under the authority of the Forest Service, primarily in the East (USFS, 1961).

Taylorism, in which the operation is broken down into its component parts and numerical values are assigned to each part. The research agenda attached to that operational breakdown sought to identify better numerical values for the component parts and smooth out some of the transitions between parts. The end goal was to prevent fires by finding them early, suppressing them quickly, and controlling the cost. His approach would soon become a national model.

A problem that confronted this approach was light burning, that is, the use of fire as a management tool for ecosystem or livelihood objectives. It was still a common practice of new settlers and farmers in the early 20th century. In the western states, the Forest Service tried to deter the persistence of light burning by systematically protecting demonstration forests and areas from fire to serve as an alternative (and presumed better) approach to forest management. In the South, woodsburning (the regular burning of forests) was viewed as a chronic, endemic problem. Demonstration forests were created to show the benefits of excluding fire from forests. However, the demonstrations showed exactly the opposite; fire exclusion was the wrong approach. The proponents of protecting forests from fire continued experimenting to prove the worth of fire exclusion. In the end, they failed and instead suppressed evidence that supported the value of woodsburning. The American Forestry Association went so far as to create the Dixie Crusaders, modeled on Billy Sunday evangelism, to roll into southern towns, set up big tents, and get people to take the pledge to swear off woodsburning. In the 1930s and 1940s, the Forest Service hired John Shea, a professional psychologist, because woodsburning seemed so illogical and resistant to the science of the day (that is, fire exclusion) that the only possible explanation for a propensity for woodsburning had to be psychological. In fact, the woodsburners in the southern towns had the right approach for managing fire in the forests in a way that preserved the function of the forest ecosystem and sustained their livelihoods.

Throughout the 1920s, the Forest Service consolidated its political position and its grasp over research. In 1921, Chief Greeley organized the Mather Field Conference, the first national conference held by the Forest Service. The topic was fire. In 1922, Harry Gisborne became the Forest Service's first dedicated fire researcher. The Clarke-McNary Act, passed by Congress in 1924, strengthened the ability of the Forest Service to work with state officials to protect forests, particularly from fire. The Forest Protection Board, established in 1928, made the Forest Service the lead federal agency for any public lands that had forests, and in the same year, the McSweeney-McNary Act established a comprehensive program of forest research in the agency, effectively making it the sole entity conducting fire research.

A large amount of resources became available under the New Deal programs of the 1930s—in particular through the Civilian Conservation Corps—to mobilize men to fight fires. It was thought that the goal of systematically controlling fire across the country could be achieved with this mobilization of labor, and science was rallied to support that objective. At that time, a great deal of research was put into fire-danger rating systems because it provided an administrative index for measuring the performance of controlling and excluding fire against field conditions.

Critics of the mission to rid forests of fire began to surface in the mid-1930s, especially among people interested in wildlife and people who wanted to reinstate traditional burning of various kinds. Nevertheless, the big western fires of 1934 inspired the Forest Service to announce an all-out policy of fire suppression, an experiment that was carried out across the country. In 1935, Chief Ferdinand Silcox put in place the "10:00 a.m. policy," which instructed foresters that every fire should be suppressed by 10 a.m. the day following its initial report. To help promote that policy, the first fire publication, *Fire Control Notes* (USFS, 1936), was produced the following year. In 1937, Alfred Folweiler published what would be considered the first textbook on fire, *Forest Fire Prevention and Control in the United States* (Folweiler, 1937).[1]

Prior to the New Deal, the Forest Service relied on fire reports. The money accompanying the New Deal provided support for fire research, including laboratories and instruments that could be hauled out to the field to measure conditions as they were. By early 1940s, wind tunnels had been developed and crib fires were being used.[2] Mechanical engineering, closely associated with Forest Service fire research pioneer Wallace Fons, was beginning to encroach on the field. World War II was a fire war, as is evident from the fires following the Hiroshima atomic strike. Pyne said that this event and the strategic bombing survey after World War II convinced many authorities that the next war would also be a fire war. Therefore, they saw a need to find ways to further weaponize fire as well as ways to be protected from it. At the time, the only people who knew anything about large-scale fire were foresters.

Immediately following World War II, Arthur Brown—who was the fire control chief for the Forest Service's Denver regional office and would become the agency's fire control chief in 1947 and fire research chief in 1950—rewrote Folweiler's text (Brown and Folweiler, 1946), in which he reemphasized that the forest fire problem of the United States was unique and that European forestry had nothing to offer in terms of solutions. American foresters had to grapple with fire, but because their training followed a European tradition, they had no serious academic basis for the challenge. That same year, S. B. Show and B. Clarke wrote *Forest Fire Control* (1953) for the Food and Agriculture Organization of the United Nations, thus exporting around the world the American experience and model of fighting forest fires.

During the Cold War years, surplus war equipment was quickly converted for use in fire protection, which facilitated the mechanization of the war against fire. In 1954, Operation FireStop was launched. Its goal was to find out if the mobilization of science that had been so powerfully demonstrated in World War II could be applied to fire.[3] Federal and state agencies, universities, and aircraft and chemical companies began to study, among other things, techniques for attacking fire from the air. Several equipment development centers were created at this time.

[1]In his presentation, Pyne made note of several prominent textbooks in fire science published between the 1930s and the present day. The textbooks can be found in his presentation, available at http://dels.nas.edu/Upcoming-Workshop/Century-Wildland-Fire-Research/AUTO-5-97-34-D?bname=besr. Accessed July 2, 2017.

[2]Crib fires are used to study the burning rate of fuel structures. Cribs are three-dimensional grids of sticks (the fuel); they are built with different stick thickness and density to learn about the burning rate of the fuel material given the spacing of that material.

[3]For more information about Operation FireStop, see Cermak (2005).

The Forest Service also became involved in other types of fire and related engineering such as the atomic bomb testing program to better understand the fires that would result. Foresters were excited about this opportunity because it gave them some credibility and newfound standing in the scientific field. The rise in standing helped launch a National Research Council committee on fire research to provide "advisory and consulting services to the Government in the establishment and conducting of a research program on the spread and control of large fires" (NRC, 1962:1). There was also investment in several mass fire projects.[4] The National Fire Coordination Study, which was the National Cohesive Strategy for Wildland Fire Management of its day, was initiated to determine what could be done to confine damage from nuclear fire. Therefore, the 1950s saw the undertaking of a number of large-scale field experiments and new disciplines involved in the study of fire—such as aeronautical engineering, mechanical engineering, and meteorology—which had not previously been a part of the fire-science scene.

More investment was put into the National Fire Danger Rating System because the system was a mechanism for bringing together this new research. The rating system was also a way of establishing national standards and performance guidelines to measure success and costs. Other scientific investments were more questionable. For example, fire scientists pursued the idea that they might end fires by suppressing lightning or modifying the weather. Notably, other countries prone to wildland fire, like Canada and Australia, did not pursue such strategies. However, this approach was effective for increasing federal investment and interest in fire science research, which helped the Forest Service establish three national laboratories in Macon, Georgia; Missoula, Montana; and Riverside, California.

One of the most outstanding fire scientists of this period did not begin his career as such. George Byram was a physicist among foresters. He worked at the Appalachian Forest Experiment Station in Asheville, North Carolina, which was not a center of fire activity when he was hired in 1936. However, his work from the 1930s through the 1960s applying physical science to fire phenomenology contributed greatly to the understanding of fire behavior.

In 1960, the Forest Service was identified in a famous study as a paragon of public administration (Kaufman, 1960). By the early 1960s, the Forest Service was a hegemon: The agency controlled directly or indirectly virtually all research on fire. "Practically every institution and exercise that involved free-burning fire had it as a member, if not a master" (Pyne, 2010:45).

Fires in the 1960s supported a Cold War mentality of civil defense. One of the first fires of this era was the Bel Air–Brentwood fire in southern California in 1961. Two images are telling about this era (Figure 3-3). The first is an image of Richard Nixon on a rooftop with a water hose (Figure 3-3A), which Pyne displayed to demonstrate that fire has always been a political project. The second is of Willard Libby, a Nobel laureate in chemistry, who had a house in Bel Air. The image shows him in a fallout shelter, which was built for $30 using sandbags and railroad ties (Figure 3-3B). However, his fallout shelter, along with his house, was incinerated in the fire. Thus, even if fire was used as a weapon, it could not necessarily be controlled.

Against the backdrop of the war in Vietnam, the campaign against fire continued. Just as war surplus equipment had been substituted for the workforce of the Civilian Conservation Corps, so information produced by the new Forest Service laboratories was substituted for the mechanical muscle of the equipment. The National Fire Danger Rating System became

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[4]Such projects included Project Flambeau, which studied nine experimental mass fires between 1964 and 1967 in Nevada and California (Countryman, 1969; Palmer, 1969).

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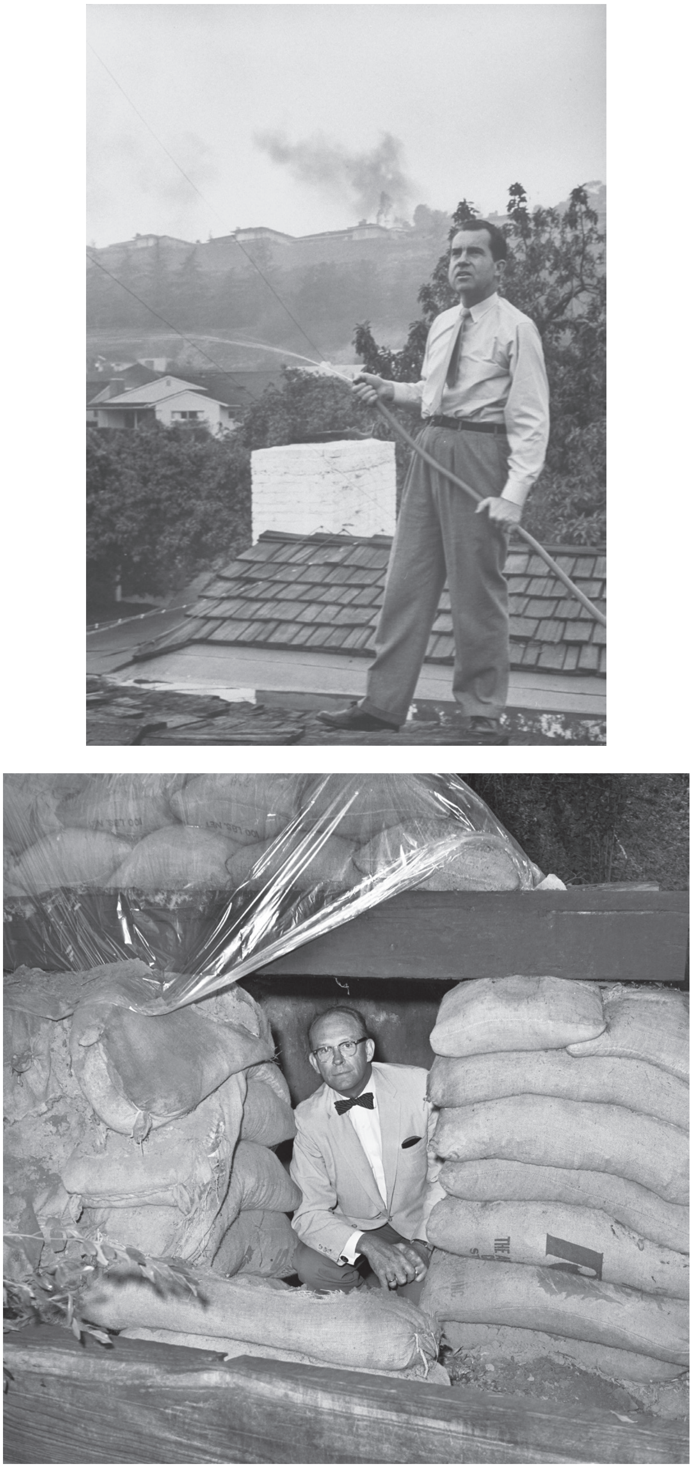

FIGURE 3-3 A, Richard Nixon on the roof of his house during the Bel Air–Brentwood Fire in 1961. B, Willard Libby in his Bel-Air bunker during the Bel Air–Brentwood Fire in 1961.
SOURCE: Pyne, slide 25. Photos courtesy of Getty Images.

a sophisticated project and now included fire behavior models. The Rothermel model in particular was a remarkable achievement; however, unwavering commitment to it may have affected the direction and outcomes of more recent modeling work. Operations research also developed during this time: the Incident Command System[5] grew out of the 1970 and 1977 fires in southern California.

However, in the 1960s and 1970s, a fire revolution was also developing. There was a large-scale protest against both the philosophy of excluding fires from forests and the institutions responsible for enforcing that exclusion. In the 1960s, federal agencies were given new charters, and some were given new categories of land, such as "wilderness" following passage of the Wilderness Act in 1964. Wilderness was defined in the law as a place "untrammeled by man" and "where man himself is a visitor who does not remain" (P.L. 88–577); over 3.6 million hectares (9 million acres) of national forest land became part of the National Wilderness Preservation System. Other federal agencies, such as the National Park Service, wanted to break the hegemon the Forest Service held over fire science so they could implement their own policies, control their own programs, and have their own branches of research. What followed these changes in management philosophy and land definitions was a fragmentation of the Forest Service's control of fire research. The Forest Service reoriented from fire control to fire management, and funding for fire research from the U.S. Department of Defense and from civil defense that had followed World War II and continued through the Cold War began to recede.

The emergence of a civil society—that is, nongovernmental entities interested in fire and forest management—accompanied this fire revolution. The Tall Timbers Research Station was an independent, privately run preserve established in Florida in 1958 to study fire on the landscape. In 1962, it held its first fire ecology conference. The conference was remarkably successful and played a key role in the insurgent movement against the Forest Service's monopoly on fire science research. In the same year, the Nature Conservancy, a nonprofit conservation organization founded in 1951, conducted its first prescribed fire. Today the Nature Conservancy manages prescribed burns on as much land each year as the National Park Service. The Forest Service pursued the traditional sense of fire as an integrated subject while the civil society researchers turned toward fire ecology.

The revolution pushed the idea that fire needed to be restored to the landscape. This central tenet led to many questions about smoke management. Thought was also given to adapting fire behavior modeling for prescribed fires and for lightning-ignited fires that could be managed in ways similar to prescribed fires.

In 1978, a big change at the Forest Service followed this revolution in thought, including in the area of research. Interagency cooperation in the federal government became vogue, though not yet in research. However, there were many new funders of fire science, including the National Park Service, other agencies in the U.S. Department of the Interior (DOI), and (to some extent) the National Science Foundation. Long-term ecological research sites

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[5]The Incident Command System (ICS) is "a management system designed to enable effective and efficient domestic incident management by integrating a combination of facilities, equipment, personnel, procedures, and communications operating within a common organizational structure, designed to enable effective and efficient domestic incident management. A basic premise of ICS is that it is widely applicable. It is used to organize both near-term and long-term field-level operations for a broad spectrum of emergencies, from small to complex incidents, both natural and manmade. ICS is used by all levels of government—Federal, State, local, and tribal—as well as by many private-sector and nongovernmental organizations. ICS is also applicable across disciplines. It is normally structured to facilitate activities in five major functional areas: command, operations, planning, logistics, and finance and administration." See https://training.fema.gov/emiweb/is/icsresource/assets/reviewmaterials.pdf, accessed August 14, 2017.

were established in 1980; they were a very different kind of demonstration forest in which fire was a part of the ecosystem. Fire ecology at this point was seen as a means of making prescribed burning and restoration possible.

The fire revolution stalled in the 1980s. Between 1978 and 1990, Forest Service research funding collapsed, in particular forest fire and atmospheric science research. Over this period, that area of research experienced a 46-percent drop in funding. However, the concept of the wildland–urban interface was developed successfully in the mid-1980s. The Forest Service led the work in this area, in part because there were no serious alternatives.

The fire revolution started up again in the 1990s. The first journal dedicated to wildland fire science, the *International Journal of Wildland Fire*, began publication in 1991. The National Biological Survey was formed within DOI in 1993 as that department's consolidated arm of biological research. A traumatic fire season in 1994 led to the Federal Wildland Fire Policy in 1995. In 1996, the National Biological Survey was subsumed by the U.S. Geological Survey in DOI, back where it began. The National Interagency Prescribed Fire Training Center was established in 1998. Statistics were collected for the first time on different categories of fire. Also in 1998, Congress appropriated funding for the Joint Fire Science Program (JFSP) to support the use of fire and fuels treatment with the goals of reducing severe wildland fires and improving ecosystem health.[6] The JFSP operates through an interagency partnership between DOI and the U.S. Department of Agriculture for research, development, and applications related to fire science, and Pyne opined that it is one of the real success stories of the last few decades. The fire revolution was pursued outside the United States as well, in nations such as Portugal, Russia, Canada, South Africa, and Brazil.

In 2000, the National Fire Plan was implemented. It allocated a good deal of funding for fire science and gave the field political attention, but it also made the treatment of fuels (for example, through thinning or prescribed burning) the only measure of action. Measurement based on fuels treatment appeals to forestry because it keeps the focus of fire science on trees rather than on fire itself. Administratively, the amount of area thinned or prescribed burned and the effects of those treatments are easier to quantitatively account for than other effective but less measurable wildland fire management approaches.

In the early 21st century, fires are bigger, more communities have burned, and firefighters have continued to die. This situation was and is truly a crisis for the Forest Service. It has led to the coinage of the term *megafire*. The wildland–urban interface has received increased attention during this period. Changes in funding or the absence of funding have created almost an existential crisis for the agency. However, at the same time, there has been an enormous expansion of disciplines within and related to fire research and an explosion of relevant publications. Therefore, while today may be the time of megafire, it may also be the meta-fire era because of the volume of research and analysis.

Nevertheless, Pyne observed that the additional research does not seem to be abating the challenges presented by fire. Where it had once been a model agency, the Forest Service has more recently been identified by people such as the political scientist Francis Fukuyama as the epitome of dysfunctional democracy (Fukuyama, 2014). Pyne said this characterization is unfair, but it nonetheless has serious effects on the national forest system because of the Forest Service's lynchpin place in that system.

In an effort to put the pieces together, the Forest Service, in cooperation with agencies from DOI, rolled out the National Cohesive Wildland Fire Management Strategy in 2014. Pyne found the strategy particularly interesting because the subtext that accompanies the

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[6]For more information about the Joint Fire Science Program, see *1998 Joint Fire Science Plan*, available at https://www.firescience.gov/JFSP_plan.cfm. Accessed July 29, 2017.

document is the recognition that the problem of managing wildland fire is political, not just policy-oriented. The strategy is a kind of fire constitution, needed to make sure all the players understand the parts they play.

Pyne displayed two graphs, one that showed the increase in the costs of fighting fires in recent years and the other showing fire publications based on the E. V. Komarek bibliography at the Tall Timbers Research Station[7] and on Web of Science (Figure 3-4). The curves of the two graphs are the same. If the money being spent on fighting fire is not changing the occurrence of megafires, Pyne noted that the same could be said about the return on investment for all the research going into fire science. Therefore, the increase in publications indicates that there is more fire science as it has been traditionally carried out, but it also indicates that more fields of science are identifying with fire. For example, the fields of remote sensing, geographic information systems, emissions studies, atmospheric chemistry, and modeling are all more involved in fire science today.

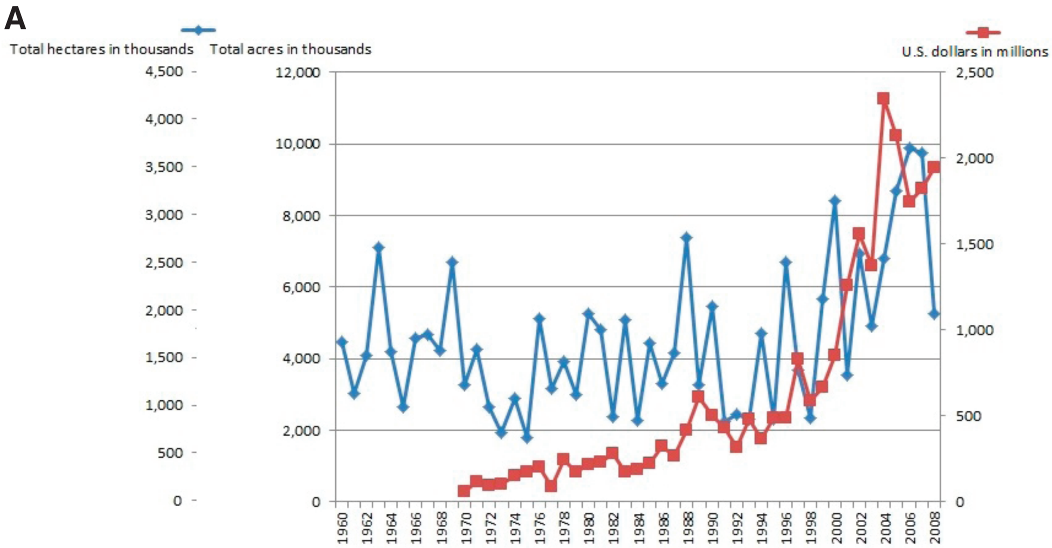
Pyne returned to where he opened, with a discussion of human civilization. Today's civilization is one based on fossil fuels. That determines where people live, the direction of climate change, and the cause of many ecological pathologies. Therefore, Pyne suggested that perhaps the Anthropocene epoch should be renamed the Pyrocene epoch. To demonstrate this point, he showed a photograph of the Tallgrass Prairie Preserve in the Flint Hills of Oklahoma. Bison freely range and there are free-burning fires, but the landscape is also filled with pump jacks and pipelines carrying oil. Even areas like the preserve are framed by a fire-driven civilization.

Traditionally fire history has been thought of as a subset of natural history, particularly climate history. Pyne suggested that in the future there may have to be a pyric inversion—an acceptance that natural history and climate history are subsets of fire history because fire is what is enabling humans to affect the planet as they are. Making this mental shift would create the possibility of a new narrative framework for fire, to give fire some autonomy as a scientific discipline.

Pyne concluded that today is an era of new ideas in fire science from many different fields. Even traditional ecological knowledge is being promoted. Fire is seen as an informing presence, if not an informing principle, although it still has no intellectual tradition of its own. Instead, fire science is funded because of the problems that fire seems to cause. The Forest Service is no longer a hegemon of fire research and fire control, and new institutions now contribute to what is known. They also have funding and agendas of their own. Fire as a topic of research and related research programs has been globalized.

Pyne predicted an opportunity for big science projects going forward, akin in scale to those undertaken in Operation FireStop in the 1950s. He suggested a FireStop II to mobilize research into how new digital technologies can be of use to fire science; an accompanying National Cohesive Strategy for Research could integrate that research with all that is known from other disciplines involved in fire science. He also suggested that, in terms of science and management, fire culture matters more than fire science. A fire culture can work with fire, with or without science. Great science is not useful if it cannot be translated into institutional cultures. Pyne proposed that it was no longer possible for science to provide information about the conditions of the past and about what future conditions will be. An inflection point has been passed and science will instead provide metrics about the changes that humans are causing and elucidate what those changes mean for the future. Fire history may also be at a major inflection point, and managed wildfire serves as a symbol. It

[7]The E. V. Komarek Fire Ecology Database. Available at http://talltimbers.org/fire-ecology-database. Accessed June 26, 2017.



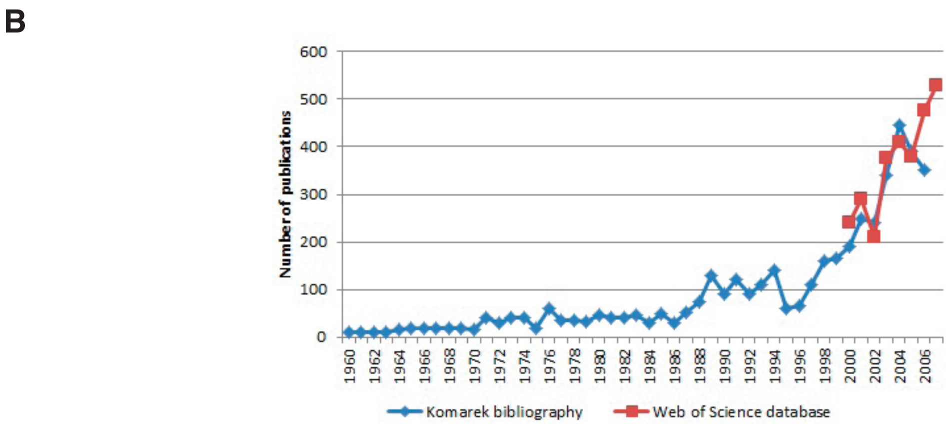


FIGURE 3-4 A, Total U.S. wildfire hectares (acres), 1960–2008, and U.S. Forest Service expenditures on fire, 1970–2008. B, Publications on fire in the E. V. Komarek bibliography, 1960–2006, and in the Web of Science database, 2000–2007.
SOURCE: Pyne, slide 41; Zybach et al. (2009); Frost (2008).

is a hybrid fire, half suppression, half prescribed burn. Pyne asked how managed wildfire should be thought of, that is, how it fits into an understanding of the relationship of science in management.

Chief Forester Dale Bosworth noted several times during his 2001–2007 tenure that fire would shape the future of the Forest Service in the 21st century, and that seems to be the case. Although the Forest Service is no longer an indispensable agency, a national system of fire management and fire research will not function without it. The agency is still a major player, catalyst, and supplier for achieving critical mass, and it is still a place where ideas will be tested in the field.

Questions. Dar Roberts began the brief question and answer session by asking Pyne about climate change. He wanted to hear Pyne's thoughts about what is to be done when climate change affects the ecological rules of the way fire operates, so that what has been learned in the past cannot necessarily be applied to manage fire in the future. Pyne said he would return to one of his opening observations, that the issues seen now are historically constructed. We cannot return to a path we left, he said, but the past tells us why our conditions today look the way they do. Observations of the past do not reveal what should be done. There was hope that fire science could guide a return to the original path. If the right science was invested in, the missing parts could be identified and the dots could be connected. However, Pyne was doubtful fire science could guide any return to an earlier path. Instead, what he sees from people in the field is that they are pursuing managed wildfire or other kinds of operations as the best options of many bad alternatives.

A participant asked Pyne whether it is good or bad that fire is not necessarily an academic discipline and is instead a problem-oriented, applied science. Pyne replied that the place of fire in academic study is a reality. Fire had a heritage in the ancient world. For Aristotle, it was a model system. The other ancient elements all have academic disciplines and whole university departments. However, this is not the case for fire. The only interest in fire as an integrated subject or as an autonomous subject will be because of problems related to it. Pyne said the absence of an academic discipline has to be accepted, and approaches are needed to bring together the varied fire interests to help understand the problem in its totality.

Another participant asked Pyne to elaborate on his vision for a National Cohesive Strategy for Fire Science Research. Pyne said that, given the variety of people and disciplines involved in fire, to avoid a continuation of the rising publication curve that does not translate into effects on the ground, a way needs to be found to bring the strengths of these various components together. He reiterated that a FireStop II model could be an effort to beta test some of these ideas. Traditionally, the Forest Service provided that kind of integration, but that has not been the case for some time.

THE ROLE OF PEOPLE IN CURRENT AND FUTURE U.S. FIRE

Jennifer K. Balch, University of Colorado, Boulder

With an opening caveat that she did not possess a crystal ball, Balch laid out her presentation's goal to provide information and perspectives from science about fire in the United States over the last few decades. Those perspectives and information are an important starting point for projecting and thinking about what future fire regimes will look like. Specifically, Balch's talk concentrated on the role of people in current and future fire in the United States. As a physical geographer and a fire ecologist, Balch has spent a great deal of time thinking about how fire works in systems, and throughout her career she has continued to come back to the important role that people play in changing fire.

The question that percolates in scientific communities these days is: When and where are hotter and drier conditions creating an opportunity for human ignitions to spread? To answer that question, Balch started by looking at what science knows now: fires are increasing in number and size. Figure 3-5 shows an imprint of fire across the western United States using a U.S. government mapping project called Monitoring Trends and Burn Severity (MTBS), which is administered by the U.S. Geological Survey National Center for Earth Resources Observation and Science and the U.S. Forest Service Remote Sensing Applications Center. Each of the colored bars represents a different ecoregion, and in all ecoregions

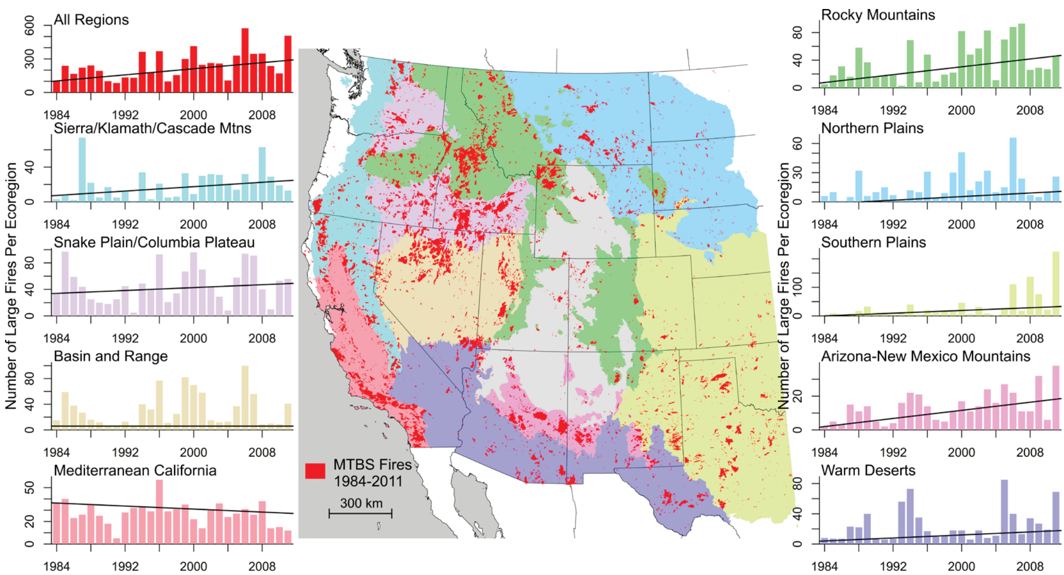


FIGURE 3-5 Western U.S. trends for number of fires over 400 hectares in size in each ecoregion per year, 1984–2011.
NOTE: Mediterranean California (pink) is the only ecoregion with a documented decline in fires.
SOURCE: Balch, slide 3; Dennison et al. (2014).

but one the number of fires has increased since the start of the data set in 1984. Evidence from a slightly different record shows that, starting in the 1970s and going to the present, the number of fires over 400 hectares (1,000 acres) has been on the rise (Westerling, 2016). This trend is linked to two important phenomena. One is temperature anomalies. The other is earlier onset of spring.

Fire scientists think about the triangle of fire, which consists of three ingredients: climate, fuels, and ignitions. While the recipe appears to be simple, variations of those ingredients and the effects of people's action on them create endless complexity. With regard to climate, recent work by Abatzoglou and Williams (2016) shows that anthropogenic climate change has resulted in more dried fuels and has doubled the amount of western forests that have burned since 1984. Abatzoglou and Williams looked at eight different metrics of fuel aridity, ranging from the Palmer drought severity index to vapor pressure deficit, which is a combination of temperature and relative humidity. In each of these eight metrics, they found that anthropogenic climate warming accounted for over 50 percent of the increase in fuel aridity from 1979 to 2015. They then linked the changes in fuel aridity to the amount of forest fire area that has burned, starting in 1984 and going through 2015. The data in Figure 3-6 show that there is a stark increase in burned areas related to specifically anthropogenic climate change and drying of fuels. Therefore, the effect humans are having on climate is changing how fire is expressed on the landscape.

The second ingredient is fuels. People have radically changed fuel structures through actions like thinning, logging, agriculture, road networks, fragmentation, and introducing invasive species. Balch focused on an example of how people are changing fuels through the introduction of the invasive species cheatgrass. In the Great Basin, it covers an area of about 40,000 km^2 and is most prominent in northern Nevada. In her work, Balch matched

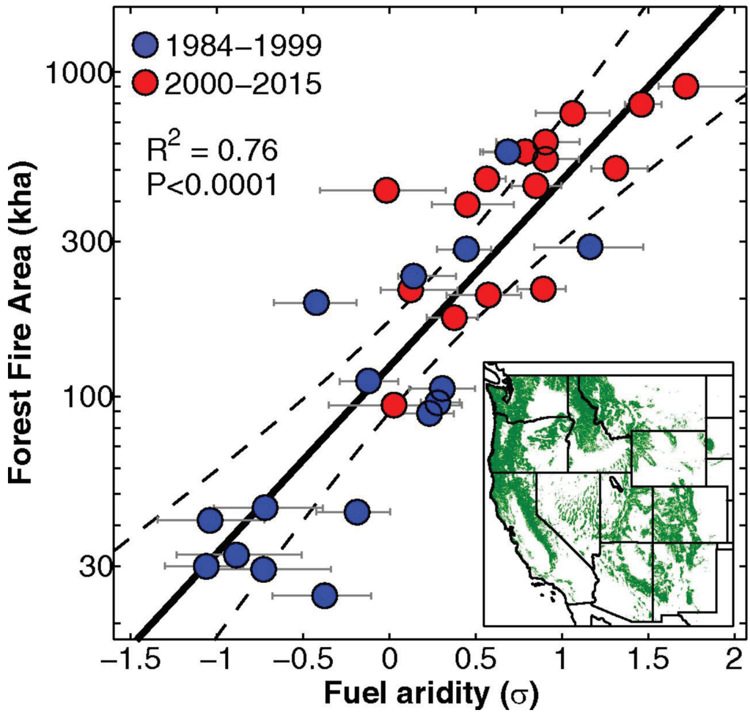


FIGURE 3-6 Annual western continental U.S. forest fire area versus fuel aridity, 1984–2015.
SOURCE: Balch, slide 7; Abatzolgou and Williams (2016).

that ground cover with the burned area measured from space by the Moderate Resolution Imaging Spectroradiometer (MODIS) to look at the relationship between cheatgrass and burning. Her work found that cheatgrass burned an area twice as large as any of the native vegetation species over a period of a decade; it accounted for about 12 percent of the total land area burned (Figure 3-7). Another example is the Hot Pot fire in northern Nevada in 2016. This lightning-ignited fire burned approximately 48,500 hectares (120,000 acres) in 30 hours; the flames spread quickly over a large area because of the carpet of cheatgrass that covered the terrain and filled in the space between native vegetation.

The third ingredient is ignitions. In the last few decades in the United States, humans have started over 84 percent of wildfires. Balch and her colleagues recently looked at the human role of fire in the conterminous United States by using the U.S. Forest Service-sponsored Fire Program Analysis fire-occurrence database (FPA-FOD), compiled by Forest Service ecologist Karen Short (Balch et al., 2017). They found that people are expanding fire's natural niche across the conterminous United States. Humans start the majority of fires and, more importantly, humans are tripling the length of the fire season by providing ignitions when lightning does not. The length of the human-ignited wildfire season in the United States is about 150 days a year, whereas the length of the lightning-ignited fire season is only about 50 days a year. Because of that influence, the wildfires that people start dominate an area seven times greater than the area affected by lightning fires, and people are responsible for 44 percent of all the area burned in the conterminous United States.

Balch and her colleagues based their analysis on the more than 1.5 million records in FPA-FOD of wildfires that were suppressed in the conterminous United States over a

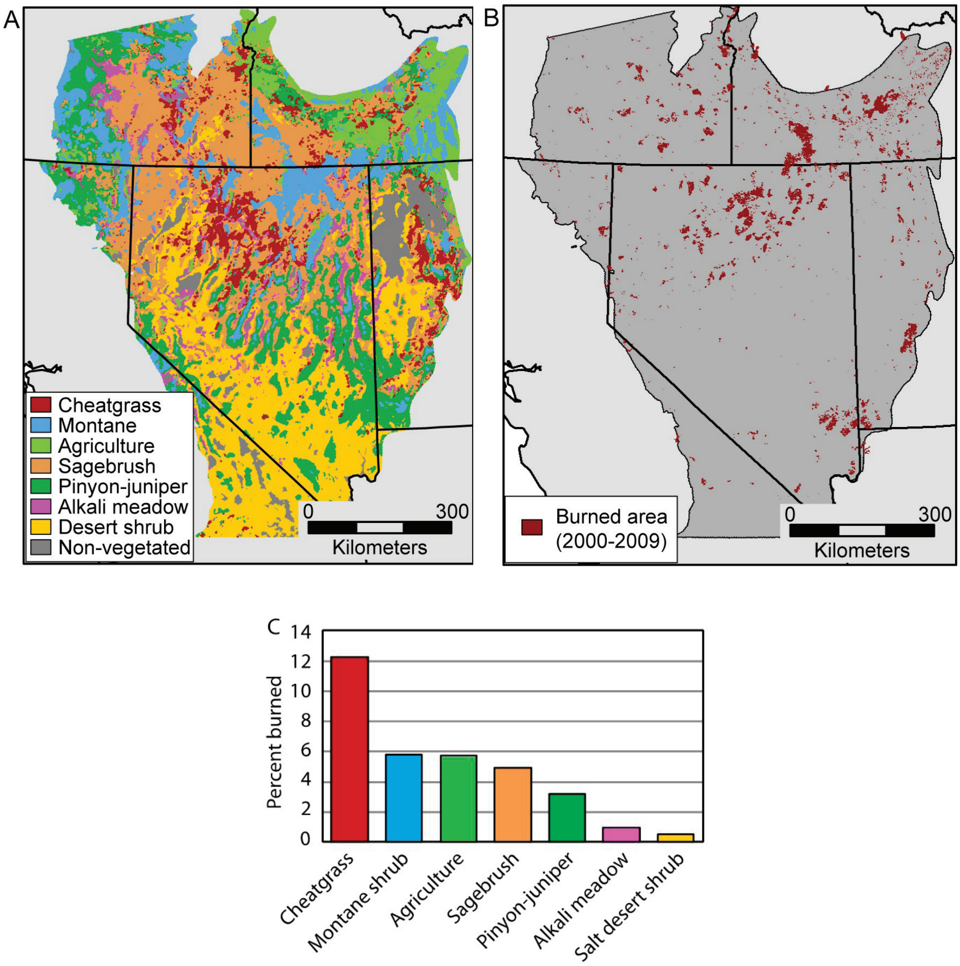


FIGURE 3-7 A, Great Basin land cover using a phenology-based land cover classification from the Advanced Very High Resolution Radiometer time series. B, Burned area from 2000 to 2009 recorded by the Moderate Resolution Imaging Spectroradiometer. C, Percent of land burned by land-cover type. SOURCE: Balch, slide 9; Balch et al (2013).

2-decade period (Figure 3-8). That database also contains information about the cause of wildfires. Of the 1.5 million records of wildfires in the database, 1.3 million of those fires were started by people, and 260,000 were started by lightning.

Balch further stated that the spatial distribution of the wildfires recorded in FPA-FOD shows the strong dominance by people as igniters of fires in both the eastern United States and in Mediterranean California whereas lightning dominates the cause of fires in the inner mountain region (Figure 3-9). The distribution displays the spatial patterning of where lightning occurs and starts fires, but it also reflects where people live, how they live, and how they are using those landscapes.

In looking at the potential for people to change and shift fire regimes, it is necessary to understand the natural sources of ignitions. Balch and her colleagues looked at the density of dry lightning strikes (occurring with less than 2.5 mm of precipitation) and the percentage

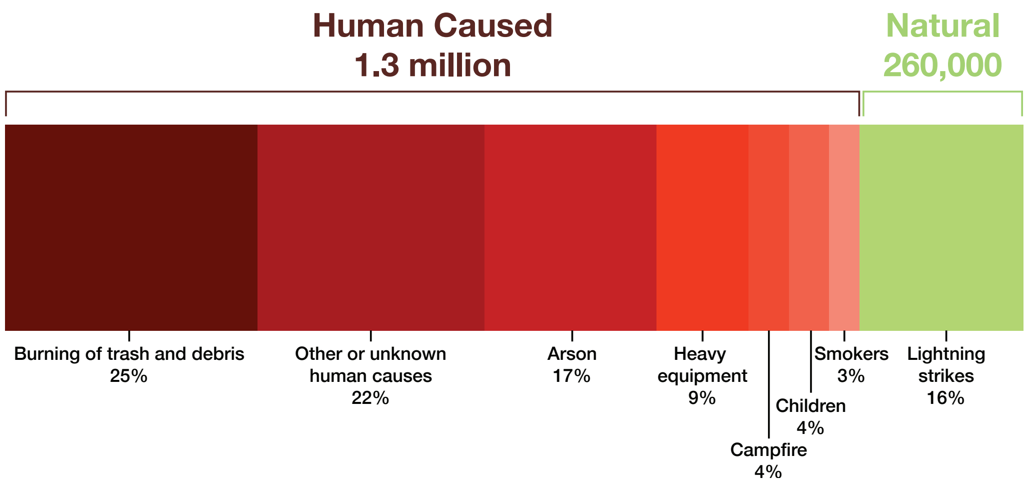


FIGURE 3-8 Major causes of wildfires in the conterminous U.S. states, 1992–2013.
NOTE: Figure includes 2013 data, which were not included in Balch et al. (2017).
SOURCE: Balch, slide 14; Balch et al. (2017). Image courtesy of Climate Central.

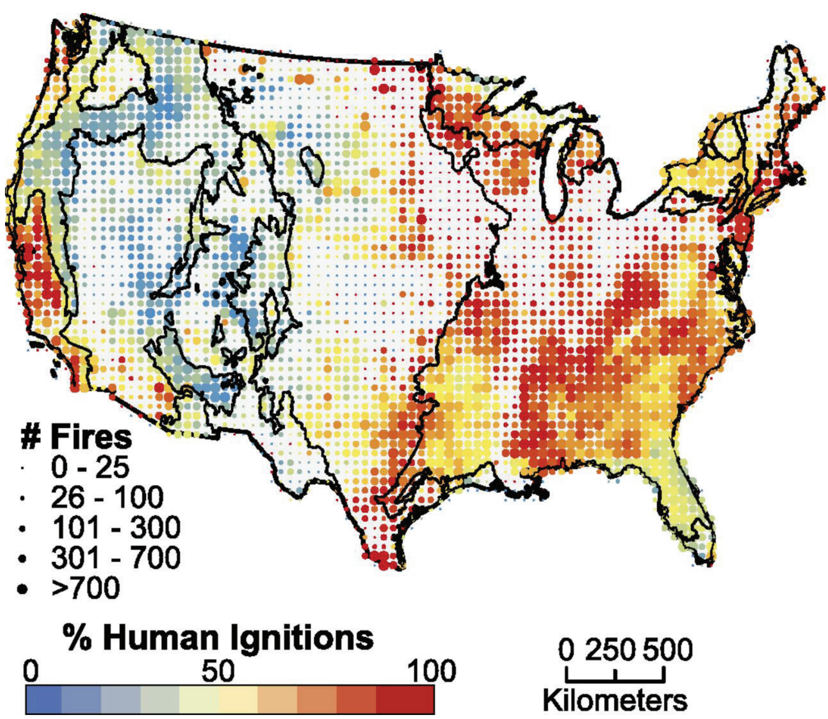


FIGURE 3-9 Spatial distribution of conterminous U.S. wildfire records in U.S. Forest Service–sponsored Fire Program Analysis fire-occurrence database, 1992–2012.
NOTE: Black boundaries delineated ecoregions.
SOURCE: Balch, slide 15; Balch et al. (2017).

of total lightning strikes that were dry lightning in the western United States between 1992 and 2013. Figure 3-10 shows a high concentration of lightning strikes in the southwestern states, many of which occurred with dry conditions, while lightning strikes were relatively absent from Mediterranean California. They found 97 percent of all fires in Mediterranean California were caused by people. This percentage is drastically different from that of the Sierra Nevadas, where dry lightning was much more common and people accounted for only 34 percent of fire ignitions.

Balch has also looked at the seasonal and temporal distributions of human-ignited fires and of lightning-ignited fires. Plotted temporally over the calendar year, human-ignited and lightning-ignited fires display noticeable patterns (Figure 3-11). The data show that human-ignited fires are prevalent in the spring in the eastern United States and common in the summer and the fall in the western United States. In Texas and Louisiana, burning occurs in all seasons. By comparison, most lightning-ignited fires occur in summer months, regardless of location. The number of human-ignited fires is high in the spring because of early spring burning in the eastern United States. After a decline that begins in mid- to late April, the number of human-ignited fires spikes on July 4; this is the day of the year with the most human-ignited fires. Balch said this phenomenon—the most fire ignitions on a single day occurring on a holiday that involves fireworks—speaks to Pyne's point about the importance of the cultural mark on fire. It is evident from the temporal distribution of fire across the year that human-caused ignitions play a large part with regard to fire, in addition to climate and fuels. Figure 3-11 shows that people are adding 850,000 fires during the times of year (spring and fall) when lightning strikes are rare. The summer distribution of lightning-ignited fires follows what is known from lightning climatology about when lightning strikes happen.

Balch pointed out that the distribution data were not exclusive to large fires. The data included any fire over 0.4 hectacre (1 acre) in size. Large fires are not the only kind of fire of concern. As an example, she mentioned the Sunshine Canyon fire, which occurred near

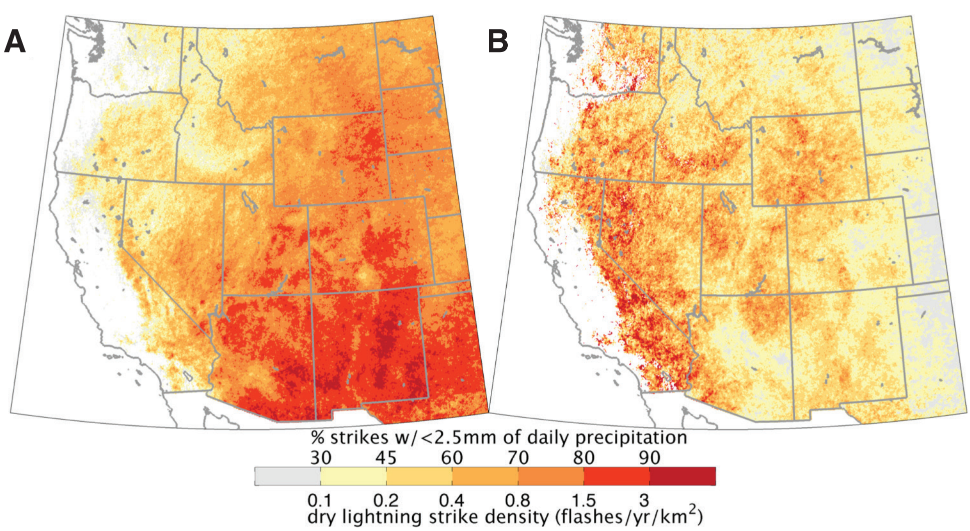


FIGURE 3-10 A, Density of dry lightning averaged over May to October, 1992–2013. B, Percent of total lightning strikes occurring as dry lightning averaged over May to October, 1992–2013.
SOURCE: Balch, side 16; Abatzoglou et al. (2016). Image courtesy of Creative Commons License 3.0.

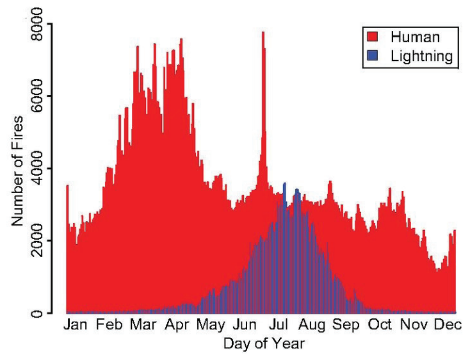


FIGURE 3-11 Frequency distribution of fire ignitions in the conterminous United States, 1992–2012.
SOURCE: Balch, slide 18; Balch et al. (2017).

her home in Boulder in March 2017, a few days before the workshop. That fire was only 30 hectares (74 acres) in size, but it threatened over 1,000 homes. As a fire ignited by people, it also serves as an example of why it is important to think about how people are vulnerable to but also contributing to fire seasons.

When the temporal distribution of fire is looked at by ecoregion, Balch noted that there is variety depending on location (Figure 3-12). People play a bigger role or a lesser role in starting fire depending on the ecoregion. For example, as she mentioned before, 97 percent of the fires that start in Mediterranean California were ignited by people, as compared to the temperate Sierras, where only 34 percent of wildfires were started by people. However, Balch observed that 34 percent is still a lot of fire ignitions by people in a region that is less populated.

Looking deeper into the data set reveals that many human-ignited fires are connected to infrastructure and practices. Road networks and human-ignited fires coincide. Human-ignited fires also overlap with where people live. However, ignition patterns differ by ecore-

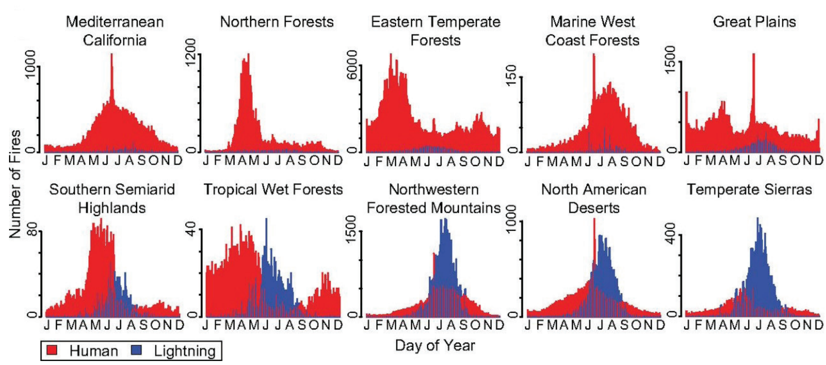


FIGURE 3-12 Frequency distribution of fire ignitions in the conterminous United States by ecoregion, 1992–2012.
SOURCE: Balch, slide 19; Balch et al. (2017).

gion; for example, the density of human-ignited fires is much higher in Appalachia than in the West because debris burning is more common in Appalachia.

In her 2017 paper, Balch and her colleagues conceptualized fire as a species akin to an animal species or plant species that has criteria and environmental conditions under which it will exist. They separated the lightning-ignited fires from the human-ignited fires and plotted two of the most important criteria or conditions: ignition strikes from lightning and fuel moisture. After plotting all of the conditions in which fires happen, not surprisingly they found that the greater the number of lightning strikes in a region and the drier conditions, the more likely a fire would be ignited by lightning. The data show that people ignited fire during moister conditions and during times when lightning strikes do not occur. When the number of fires is plotted against fuel moisture for human-ignited fires and for lightning-ignited fires, the data reveal a pulse of human-ignited fires when fuel moisture is between 14 percent and 22 percent while few lightning-ignited fires occur at this range of moisture level; this demonstrates that people are providing the ignition source in moister conditions (Figure 3-13).

When they looked at large fires—those that are over 400 hectares (1,000 acres)—Balch and her colleagues found results similar to those of other fire-science efforts that have been focused on a record of large fires provided by the MTBS project. Large fires increased between the early 1990s and the early 2010s whether they were caused by humans or by lightning (Figure 3-14). Questions that are important for the fire science community to answer are: Why are human-ignited fires increasing? Are they increasing because the climate is warming and humans are providing the ignitions that a warmer climate then translates into larger fires? Are they increasing because more people are living in landscapes that can carry fires?

Examined by season, the data show that large fires are increasing to different degrees, depending on the season and the source of ignition. The increase in large lightning-ignited fires occurs mostly during the summer season, while the increase in human-ignited fires occurs in both the spring and the summer. Balch said that was important to know because, if there is an early spring onset of large fires, is it lightning that is providing those ignition sources, or is it people that are providing those ignition sources for fires to start?

Balch then posed the questions: What do these data and trends mean for the future of fire in the United States? Will the fire season contain more large and destructive fires going into the future? Before exploring those questions, Balch stressed that not all fire is bad. Fire benefits ecosystems. The message from all the recent work that she presented is not that more fires need to be put out; instead, more of the right kinds of fires need to burn. The re-

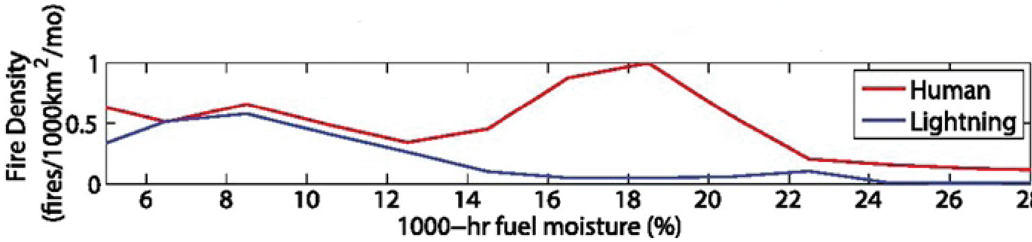


FIGURE 3-13 Histogram of 1,000-hour dead fuel moisture and lightning strikes, respectively, for human-ignited and lightning-ignited fires.
SOURCE: Balch, slide 21; Balch et al. (2017).

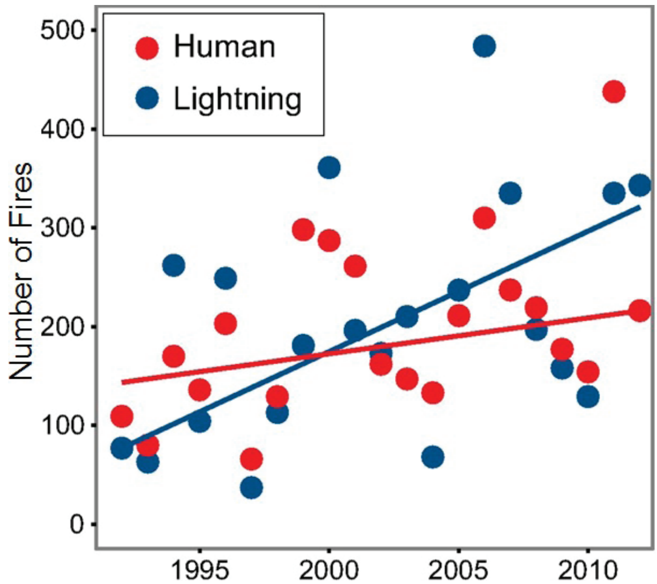


FIGURE 3-14 The number of human-ignited and lightning-ignited fires over 400 hectares in size in the conterminous United States, 1992–2013.
SOURCE: Balch, slide 22; Balch et al. (2017).

search shows that people are providing the ignition source for 84 percent of wildfires, so the next step is to think about how humans can influence the ignition of the right kinds of fires.

A key question that will need to be answered to understand what the future of fire will look like is how climate change will interact with people. Current research may be able to answer this question, and this area is also a research frontier. Balch and colleagues have matched human-ignited fires and lightning-ignited fires with the current scientific understanding of how short-term fire danger is changing because of climate change, so they can look at the intersection of people and climate with regard to fire. Work by Moritz and colleagues has projected future climate scenarios and how future fire activity will change given those scenarios, going from 2010 to 2039 to 2099 (Moritz et al., 2012; Figure 3-15). Those projections show that fire activity in the United States will likely increase relative to climate variables.

Another key piece of data needed to make predictions about the future of fire in the United States is information about where people live and where they are going to live in the future. About 10 percent of the conterminous United States' current land area is wildland–urban interface (WUI), where houses are intermixed with wildlands (Figure 3-16). That percentage is projected to double by 2030. Furthermore, it is estimated that 80 percent of the land that could end up falling into the WUI is not yet developed. These projections need to be taken into account when thinking about where people are going to be the sources of ignition in the future and where they will be vulnerable to changing fire regimes. It is worth noting that, even with only 10 percent of the land in the WUI, thousands of structures were lost to wildfire between 1999 and 2011 (Figure 3-17). Many of these fires were started by people. Balch observed that humans create vulnerable structures and vulnerable infrastructure which are also vulnerable to human-ignited fires.

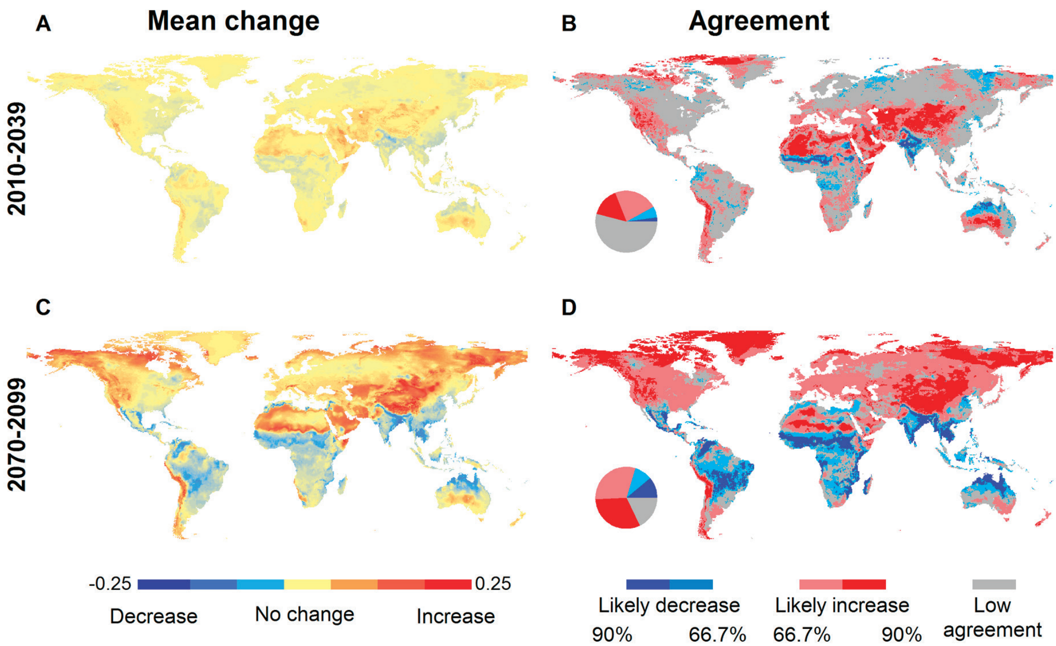


FIGURE 3-15 A, Mean change in predicted fire probability among the 16 global climate models (GCMs) for 2010–2039 (change assessed from baseline probabilities 1971–2000). B, Degree of model agreement in predicted fire probability among the 16 GCMs for 2010–2039. C, Mean change in predicted fire probability among the 16 GCMs for 2070–2099. D, Degree of model agreement in predicted fire probability among the 16 GCMs for 2070–2099.
SOURCE: Balch, slide 27; Moritz et al. (2012). Image courtesy of Creative Commons License 3.0.

The projections of the future show that it will be important for humans to coexist and live more sustainably with fire. Because people in the United States live so close to flammable places and flammable landscapes, how people build and how people use fire will be important. Data aggregated by Headwater Economics identified over 4,000 U.S. communities that are located within 10 miles of where a fire of at least 40 hectares (100 acres) occurred between 2000 and 2014 (Headwater Economics, 2016). This proximity to fire justifies the need for communities to be "fire-wise" and for infrastructure to be better adapted to flammable places.

One idea for better adapted infrastructure is to borrow the concept of floodplains and create fire plains. Fire plain maps would provide data for incentives or disincentives connected to building. Such maps could be created for the entire country, much like the Federal Emergency Management Agency's flood maps. California has been a leader in this work, putting together *fire hazard severity zones* to guide building in flammable landscapes. Information contained in Cohesive Wildland Fire Management reports about the frequency and severity of fire in different fire regime groups provides justification for fire plain maps.

In terms of how people use fire, Balch said fire science has enough data to support conducting more fires that have ecological benefits. The Coalition of Prescribed Fire Councils reported that over 47,000 km^2 or roughly 12 million acres were treated with prescribed fire in 2014 (Melvin, 2016; Figure 3-18).

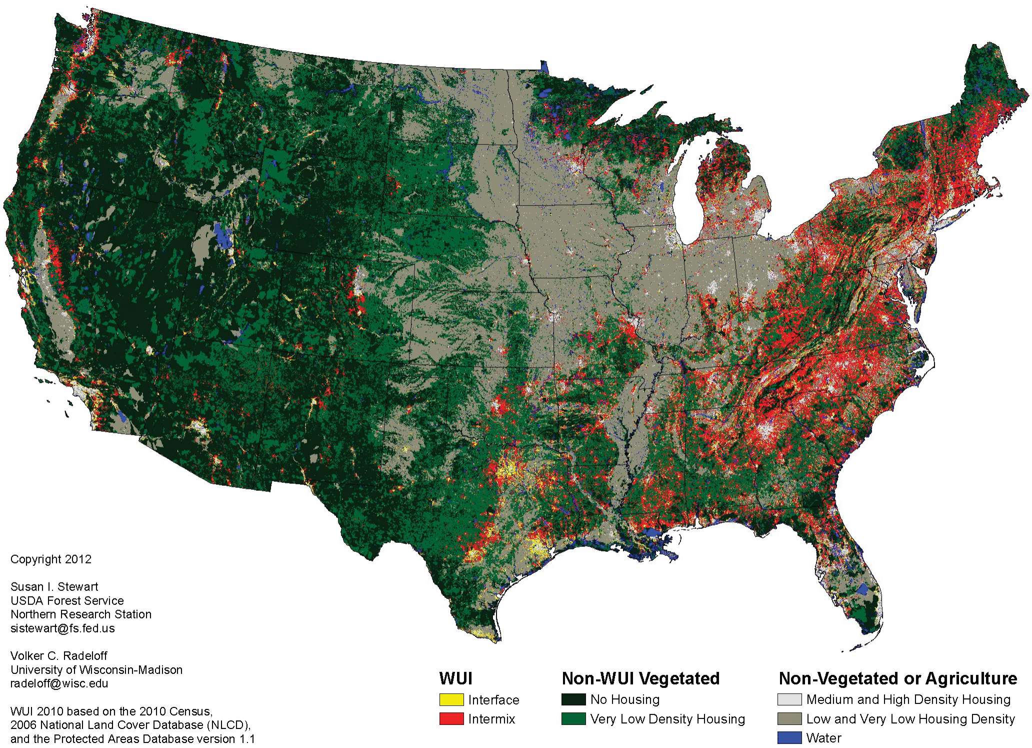


FIGURE 3-16 Wildland–urban interface in the conterminous United States, 2010.
NOTE: Yellow and red indicate the places where people are living in the interface.
SOURCE: Balch, slide 28; Radeloff et al. (2005). 2010 map available at http://silvis.forest.wisc.edu/maps/wui. Accessed June 28, 2017.

Some important lessons about adapting to living with fire come from communities around the world who are practicing patchwork mosaic burning and using it as a mechanism to reduce the risk of large climate-driven fires. For example, in Western Australia, the landscape around the Martu indigenous communities is a patchwork of lightning-ignited fires and smaller managed burn systems from aboriginal hunting fires (Bird et al., 2012). The community is effectively mitigating the risk of large climate-driven fires through their use of human-ignited fires. Such mitigation is justification for doing more of the right kinds of fire and using prescribed fire as a tool rather than treating fire as a threat. However, Balch acknowledged that it is difficult institutionally to incorporate that type of distributed network of prescribed burning back into the daily events of landscape management in the United States.

Balch also touched on the role of scientists and the power of big fire data. She conceptualized the metaphor of a modern day palimpsest. A palimpsest is a manuscript page from a scroll or book that the text has been scraped or washed off so that it can be used again. She likened the U.S. landscape to a living palimpsest that has imprints and memories from past uses of the landscape, from human use of fire, and from fire being part of that landscape. Today's field of fire science is also a palimpsest because there is information and data from different sources that can help answer important questions about the future of fire. Scien-

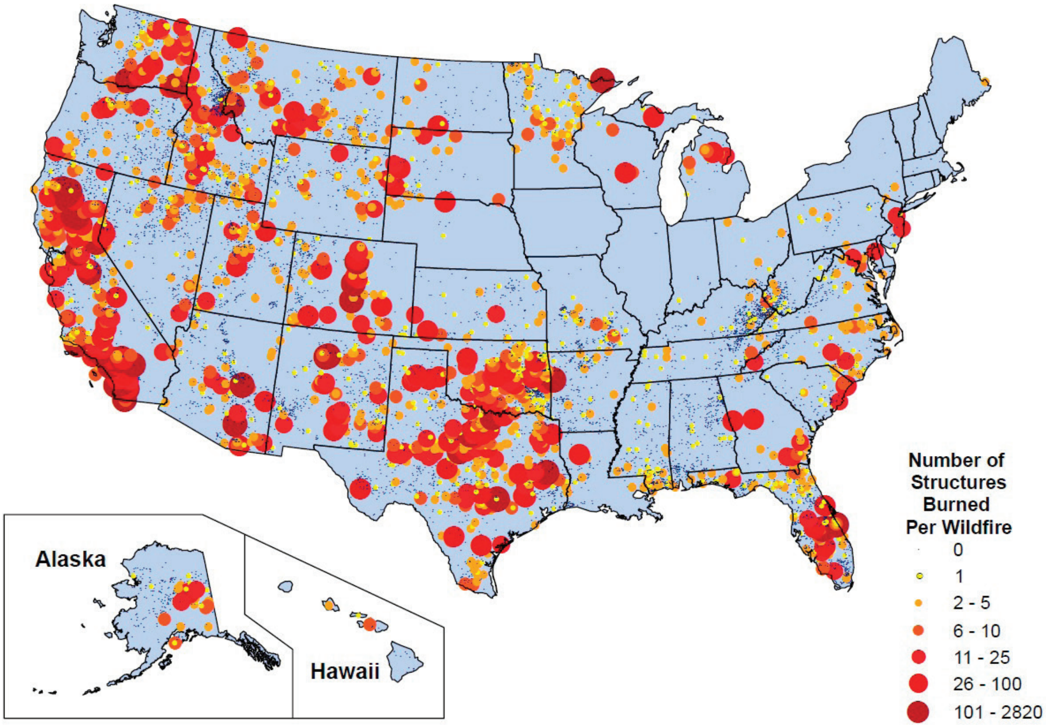


FIGURE 3-17 Structures lost to wildfire in the United States, 1999–2011.
SOURCE: Balch, slide 29; data compiled and mapped by the U.S. Forest Service Fire Modeling Institute.

tists have at their fingertips information spanning from the map of forest fires that Charles Sargent gathered in the 1880 census (Figure 3-2) to satellite imagery from multiple systems that, when combined, provide incredibly powerful visualization tools for looking at the fire landscape. There are also novel sources of information such as machine learning techniques and text analysis or natural language processing. These tools can be applied to incident reports from different agencies to mine the information in those reports for novel insights. Drones are another tool that will help scientists better understand ecosystem processes at a finer scale. Finally, social media data, such as searches for the term *wildfire*, help scientists understand social responses to wildfires.

Balch concluded with three major points to help reframe fire myths to realities. First, people play a fundamental role in changing fire, in concert with climate and fuels. Second, not all fire is bad; it can do good work in ecosystems. Third, people can and must live with fire and can do so by building better and making better use of fire.

Questions. Balch was asked whether fires started by human infrastructure were included in the number of human-ignited fires. The questioner pointed to the fires that burned in Gatlinburg and elsewhere in Sevier County, Tennessee, in the fall of 2016 as an example. While one fire was started by arson, many fires were caused by power lines. Balch responded that causes related to human infrastructure, like power lines and railroads, were included in the data set as categories and even subcategories. She said power lines are an important

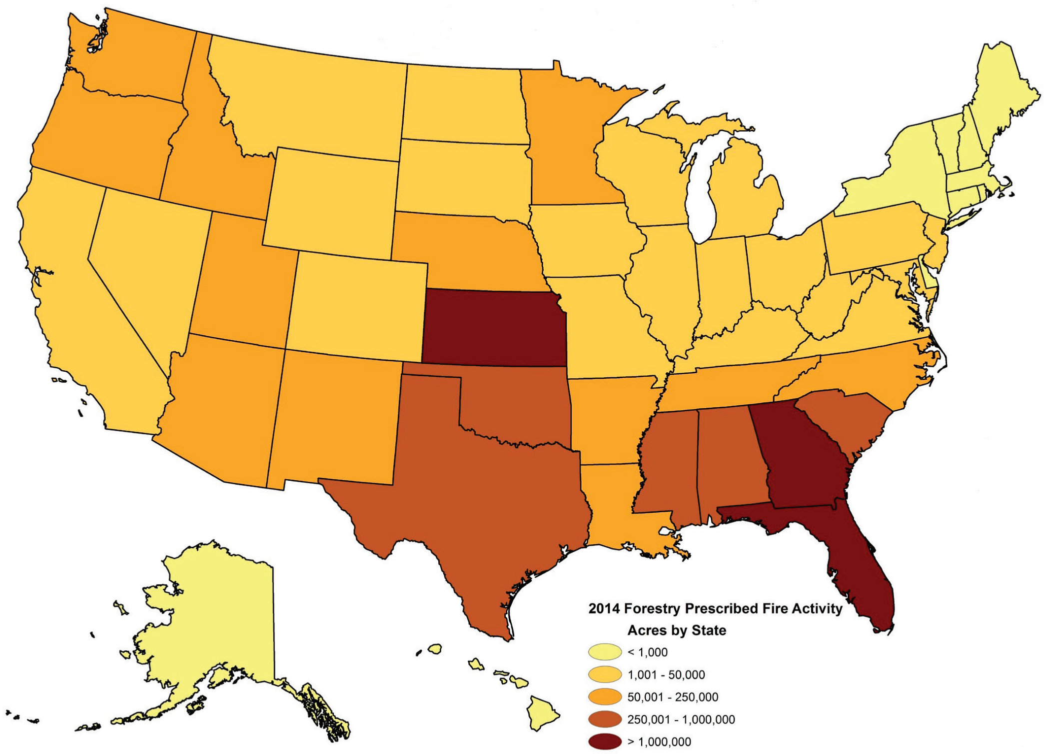


FIGURE 3-18 Acres of all prescribed fire use by state, 2014.
SOURCE: Balch, slide 34; Melvin (2016).

ignition source, particularly during hot and dry conditions when people are running air conditioners. When the power lines become overloaded, they ignite new fires. Fires caused by such events are emblematic of some of the fire problems the United States is experiencing.

A participant asked if Balch had looked at the interior of Alaska and the change that is happening there. Balch replied that her 2017 study did not include Alaska because other good work that looks at the role of human- and lightning-ignited fires in Alaska has already been done. She also noted that there are many important cultural differences reflected in the data on Alaska.

Another participant wanted to know the source of the data in Balch's 2017 paper. He also wondered if Balch had found a way to relate that data to satellite data. With regard to the satellite data, Balch said she is currently working on matching government records of wildfire with satellite data from MODIS, Landsat, and the Visible Infrared Imaging Radiometer Suite. She is finding that there is not complete congruence between the data sets. There are fires in the government record that are not seen in the satellite records and vice versa. She said this lack of congruence points to the need for an Uber-style data set on fire, in which all these different sources of information are combined to get a full picture of fire. The source of the data for her 2017 study was the Fire Program Analysis fire-occurrence database, which Karen Short compiled and integrated. Balch noted that Short works for the Forest Service and should be acknowledged for her work because it opened the door for the type of inquiry pursued in the 2017 study. Short deserves credit for putting so much effort and dedication into compiling this information and reducing the number of redundant records.

Another participant noted that one of Balch's figures (Figure 3-5) showed different ecoregions in North America, and fires were increasing in every ecoregion in the United States except Mediterranean California. He asked if anything from her analysis could explain why that was the case. Balch replied that she did not know why fires decreased in Mediterranean California, and she hoped that the audience at the workshop could help answer that question because important lessons are likely to be learned.

4

Understanding Fire: State of the Science and Research Priorities

The presentations of the first panel focused on understanding what the current state of fire science is and on the research priorities that are important for fire science. The four presentations were followed by a discussion session moderated by planning committee member Monica Turner.

FIRE REGIMES AND THE ECOLOGICAL ROLE OF FIRE IN U.S. LANDSCAPES

Meg A. Krawchuk, Oregon State University

Krawchuk said fire ecology covers a great number of ideas about natural and human fire history and fire effects on the environment, species, ecosystems, and landscapes. She presented five topics that represent that state of the science for thinking about fire ecology: (1) domain, (2) variability, (3) temporal and spatial heterogeneity, (4) mosaics, and (5) ecological response.

With regard to domain, Krawchuk said it is well recognized that fire plays an integral ecological role in ecosystems, but it has different tempos depending on location. Fire creates opportunities for the dynamisms of succession, that is, for ecosystems to progress and change over time. It also plays an important role as a disturbance in ecosystems, but that disturbance is only helpful to an ecosystem if it is the right kind of fire. Too little fire, too much fire, or the wrong kind of fire has the potential to put ecosystems out of their "natural balance."

Fire on a landscape exists as part of a fire regime, which is the range of variability in fire characteristics in a given area over a set period of time. Fire ecologists ask questions to discern what the fire regime is:

- How often does an area burn?
- Where in the vegetation does it burn?
- What caused the fire?
- How large of an area is affected?

- How much biomass was consumed and in what pattern?
- How much biomass was left behind?
- When in the year did the fire occur?

The answers to these questions tell fire ecologists about *frequency*, *type*, *cause*, *size*, *severity*, and *seasonality* of the fire regime.

Temporal heterogeneity needs to be thought of in terms of the historical range of variability in fire regimes as well as the contemporary range of variability and how those present characteristics differ from the historical range. The future range of variability needs to be taken into account as well. In terms of spatial heterogeneity, Figure 4-1 illustrates historical fire regimes in the conterminous United States. Krawchuk noted that it is helpful to look at the locations and groups of fire regimes in Figure 4-1 and then at corresponding images of landscapes indicative of these types of fire regimes (Figure 4-2). The images provide examples of historical fire regimes in the United States. For instance, frequent surface fires in

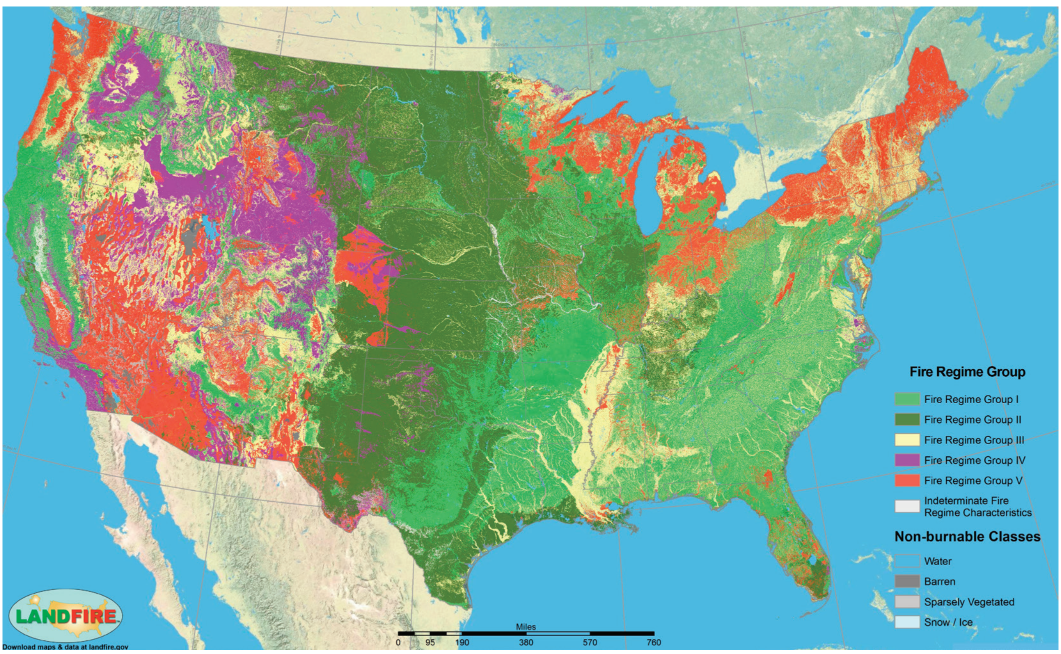


FIGURE 4-1 Historical fire regimes in the conterminous United States.
NOTE: Fire Regime Group I: burn frequency 0–35 years, burn severity generally low, replacing less than 25 percent of the dominant overstory vegetation, can include mixed-severity fires that replace up to 75 percent of the overstory; Fire Regime Group II: burn frequency 0–35 years, burn severity high, replacing greater than 75 percent of the dominant overstory vegetation; Fire Regime Group III: burn frequency 35–200 years, burn severity generally mixed, can also include low-severity fires; Fire Regime Group IV: burn frequency 35–200 years, burn severity high, leading to replacement; Fire Regime Group V: burn frequency more than 200 years, burn severity varies but leads to replacement. See https://www.firescience.gov/projects/09-2-01-9/supdocs/09-2-01-9_Chapter_3_Fire_Regimes.pdf. Accessed August 14, 2017.
SOURCE: Krawchuk, slide 4; Fire regime group map, available at https://www.landfire.gov/lf_applications.php#maps. Accessed June 29, 2017. Image courtesy of the U.S. Department of Agriculture and U.S. Department of the Interior.

FIGURE 4-2 Photographic examples of historical fire regimes in the conterminous United States.
SOURCE: Krawchuk, slide 5. Photos courtesy of Meg Krawchuk.

grasslands and frequent surface fires in dry forests are considered to be the historical norm, and infrequent crown fires in wet and cool forests are within the historical range of variability. Building on Balch's point that fire can have benefits to ecosystems, Krawchuk said it is important to realize that there is a place for fire in landscapes, even large crown fires, which are needed to replace tree stands.

Fires create mosaics, both in terms of the structural and spatial heterogeneity within the fire and the variability left on the landscape after the fire. This fourth topic of fire ecology concerns fire severity, which accounts for the organic matter lost from burning, including soil and vegetation components. It also concerns fire legacies—what is left behind and what persists through fire—such as seed banks, standing live and dead vegetation, carbon pools, and resprouting capacity. These structural and life-history adaptations act as the ecological memories that help an ecosystem return back to its pre-fire state.

Fire is one factor in the environmental niche of a species, and an important one contributing to where species occur, persist, and reproduce. Living things have adaptations that enable them to persist within a given fire regime. Fire acts as a filter, influencing who lives where; organisms are well adapted to or even dependent on certain types of fire. Figure 4-3 illustrates the relationship between fire regimes and the biotic membership within those ecosystems; the safe operating space for fire regimes and biota is where the fire regime adaptive traits match quite well with the characteristics of the box of fire regime. Krawchuk concluded by asking: Are humans leaving safe operating space for ecosystems to respond to fire as they have done historically within a given fire regime? To what degree is contem-

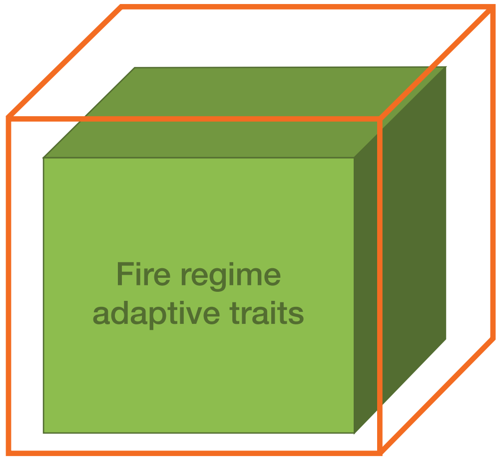


FIGURE 4-3 Conceptual representation of safe operating space supporting ecosystem resilience.
SOURCE: Krawchuk, slide 7; adapted from Johnstone et al. (2016).

porary management and ongoing climate change generating a mismatch between ecological communities and fire regimes?

PREDICTING AND MAPPING FIRE AND FIRE EFFECTS

Mark A. Finney, U.S. Forest Service Missoula Fires Sciences Laboratory

Finney's overview of fire prediction and mapping began with the following observations about wildland fire in the United States:

- Ninety-five percent of the area burned in the United States (including Alaska) each year stems from only 3 percent of the 80,000 fires that occur each year; the other 97 percent of fires are suppressed.
- The burned area covers 1.6–4 million hectares (4–10 million acres) each year.
- Fire response is the responsibility of multiple agencies at the federal, state, county, and city levels.

All of this fire has created a great deal of demand for many decades for fire prediction and for mapping. Today there are a number of tools for prediction and mapping, including systems, models, tools, data, and maps.

With regard to prediction, scientists model different timeframes and spatial extents. The main areas in prediction are operations, which includes predicting where active fires will go. Planning is also involved in prediction and encompasses risk analyses, fire management plans, and fuel treatment analysis and design. Training is another piece of the puzzle because fire prediction is part of how firefighters learn to be safe on the fire line. Finally, prediction includes research into different kinds of ecological models.

The basis for this practice of prediction in the United States is the Rothermel Spread Equation published in 1972, which is based on the culmination of a decade or more of laboratory and field research in the Forest Service's Missoula laboratory. The model has practical inputs, is fast, and produces reasonable outputs even though it has major limitations, such as the kinds of data and detail that can be ingested, the behavior of the fires that can be simulated, and its output's fidelity with respect to the actual fire.

Before computers, people used maps, nomograms, calculations of spread rates, and the vectoring of slope and wind effects to produce a fire growth map. Today this work is done by computer systems; one of the best developed is the Wildland Fire Decision Support System built in 2009. All fires under the jurisdiction of the federal government are entered into this system. It provides access to models, data, and decision frameworks and generates fire growth projections, fire behavior calculations, and probabilistic predictions that can be overlaid with values at risk. Infrastructure such as homes, power lines, bridges, and gas lines can be worked into the map. The system outputs provide a true risk framework.

An advantage of such a system is that statistics can be compiled on usage. In the 8 years the Wildland Fire Decision Support System has been in operation, it has run 43,000 analyses for about 4,000 fires, or roughly 500 fires per year. Only 3 percent of the fires on federal lands receive any kind of analysis, and it is not a coincidence that those 3 percent are the same 3 percent that burn 95 percent of the acres because all the other fires are put out; there is no point in modeling fires that do not spread. Less than 1 percent of all the fires in the United States (those on federal lands as well as on nonfederal lands) get any kind of modeling support.

Another type of analysis, which is part of the planning phase of prediction, is risk analysis. Running Monte Carlo simulations on tens of thousands or millions of fires over many different synthetic years creates probabilities of distributions of fire behavior which can then be calibrated with observed fire behavior, size, and number. Figure 4-4 is an example of the amount of computational effort that goes into such a simulation.

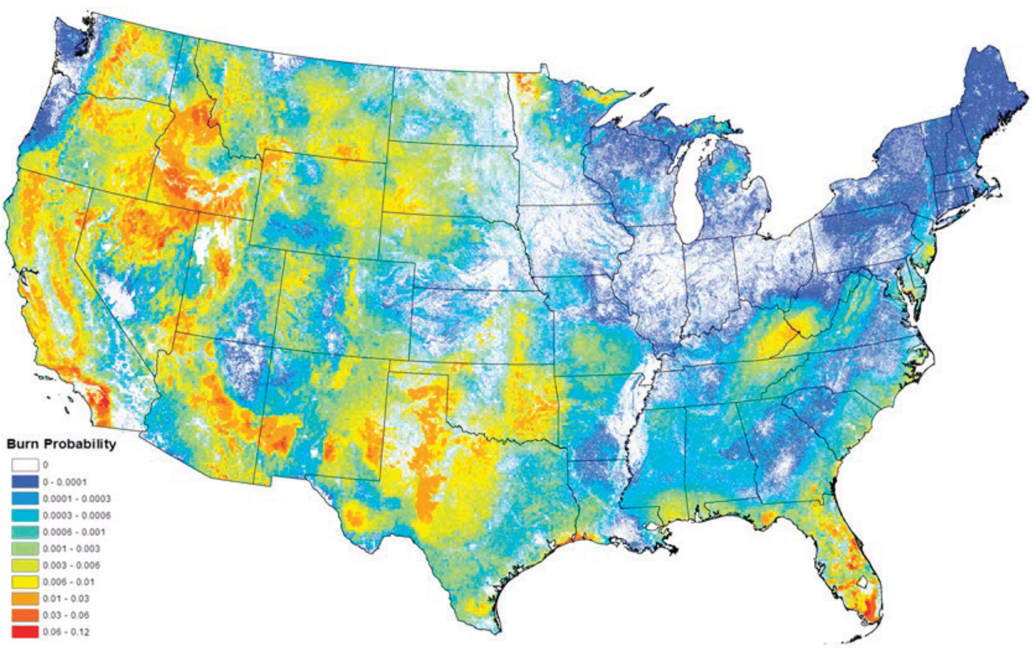


FIGURE 4-4 Burn probability map of the conterminous United States composed of 94.5 million simulations of fire.
SOURCE: Finney, slide 10; Fire Program Analysis Project, U.S. Forest Service–Missoula Fire Sciences. Available at https://www.arcgis.com/home/item.html?id=1fb27ff2aada4a68ac8078bca4fc6480. Accessed June 30, 2017.

The National Fire Danger Rating System is another analysis tool that produces many different maps daily and multiple times a day. It is accessed through the Wildland Fire Assessment System. The Rothermel Spread Equation is the foundation of this system as well.

There are also models for determining fire effects at the stand level, multistand level, and landscape level. Analyses exist that can incorporate fire behavior and fire prediction to understand what consequences such variables will have, for example, on a fire or how fuel treatments should be designed.

In sum, although it consists of operations, planning, training, and research, 98 percent of the effort in modeling is in the planning phase. Most of the fire modeling currently under way in the United States is not associated with active fires. There are not that many fires to model and the decision space—that is, what kind of actions can be taken with those active fires—is narrowed by politics.

Finney then moved on to mapping. There are many kinds of mapping efforts, such as fuel mapping, fire danger rating, satellite fire detection (for example, with Moderate Resolution Imaging Spectroradiometer [MODIS] and Visible Infrared Imaging Radiometer Suite [VIIRS]), the MTBS record (see Figure 3-5), Burned Area Emergency Rehabilitation, and airborne infrared through the national infrared operations. Starting with fuel mapping, LANDFIRE (Landscape Fire and Resource Management Planning Tools Project) is operated by the Forest Service and the U.S. Department of the Interior and provides landscape-scale geospatial data to produce vegetation, wildland fuel, and fire regime maps (see Figure 4-1). It is the basis for almost all fire decision support systems in the United States. It has 20 layers of vegetation and fuel-related information and is updated every 2 years. With regard to fire danger rating, the Advanced Very High Resolution Radiometer satellite imagery provides greenness information at 1-km resolution. In terms of satellite fire detection, MODIS imagery allows people to look at large fires in detail. Finney demonstrated through a series of images how MODIS images showed that, after a 2002 fire, areas in which fuel treatments were performed before the fire were green with vegetation following the fire compared to other burned areas. MTBS, administered by the U.S. Geological Survey (USGS) National Center for Earth Resources Observation and Science and the U.S. Forest Service Remote Sensing Applications Center, maps all fires greater than 400 hectares (1,000 acres) in the West and 200 hectares (500 acres) in the East. Additionally, there are several new technologies assisting mapping efforts, including remote-sensing tools (such as LIDAR), images from unmanned aerial vehicles, and numerical simulations (for example, gridded wind fields and high-resolution gridded weather).

With all these tools, Finney posed the questions: What is holding back practical advances in prediction? Why are these tools not being used in operational predictions? The biggest hurdle, he said, is limited knowledge about how fire spreads. The physical and empirical models do not resolve the physical processes that produce fire spread and behavior. Finney cited examples from a couple of papers to illustrate his point that understanding the processes involved in fire behavior and spread is still a scientific challenge (Clark et al., 2003; Sullivan, 2009). The question about fire spread should be answerable, but if how fire spreads is unknown, then it is hard to take advantage of all the data collected through remote sensing.

Fire spread is a nonstop reaction involving combustion and energy release that causes heat transfer to ignite new fuels that then feed back into the spread process (Figure 4-5). The challenge is that the reaction from heat transfer to ignition is operating at minute temporal and spatial scales, less than a second in time and smaller than a millimeter. Finney provided an example of the difficulty of understanding fire spread. He postulated a wildland fire, the radiant heat of which can be duplicated by a simple chicken heater for a garage. If fine

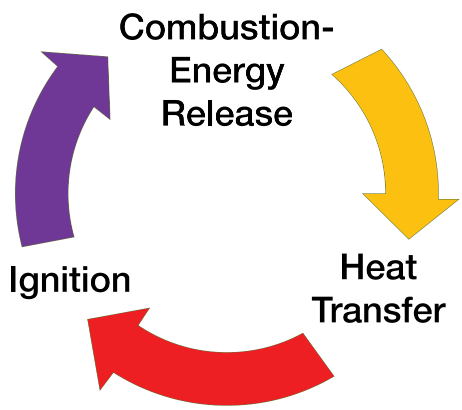


FIGURE 4-5 Cycle of fire spread.
SOURCE: Finney, slide 27.

particles (about a millimeter thick) and a wooden block (38x25x13 mm) are put next to the heater, which will ignite first? Contrary to expectations, the wood block will ignite in less than 30 seconds and the fine particles will not light at all.

CHANGING ENVIRONMENTAL DRIVERS, TIPPING POINTS, AND RESILIENCE IN FIRE-PRONE ECOSYSTEMS

Craig D. Allen, U.S. Geological Survey New Mexico Landscapes Field Station

Allen began by noting that in the last few decades forests in the West have experienced an increase in tipping point–type changes in terms of fire behavior and forest disturbance processes. Such changes include more high-severity fire and more vegetation die-off in forests. However, they are understandable because they correspond to changes in the environmental drivers that affect the components of fire, that is, atmospheric conditions, ignition, and fuel (Figure 4-6).

Environmental drivers related to atmospheric conditions are numerous and include temperature, humidity, precipitation, and wind. The number of such drivers is one of the reasons that the modeling Finney reviewed is so difficult. Any of them can drive big changes in fire behavior. Additionally, changes in atmospheric conditions involve both short-term fire weather and longer-term climate variability and directional change in climate. Examples of tipping points or nonlinear changes related to atmospheric-condition drivers are the increases in fire frequency and in the area burned related to warming in the western United States.

In terms of fuel, the type of fuel (for example, grass, shrub, or tree), the quantity of fuel, the horizontal connectivity and vertical structure of fuel, and the moisture content are just some of the environmental drivers that are undergoing change. Allen pointed to the "grassification" of the American West as an example. Bare inner spaces between perennial plants and woody plants in western desert areas are filling in with nonnative grasses, which causes change in fire behavior that the local flora and ecosystems are not adapted to.[1] Another example is the drought- and heat-induced stress on conifers and the associated insect outbreaks that have caused immense mortality in western North American forests in

[1]See also Balch's discussion of cheatgrass in the Great Basin in Chapter 3.

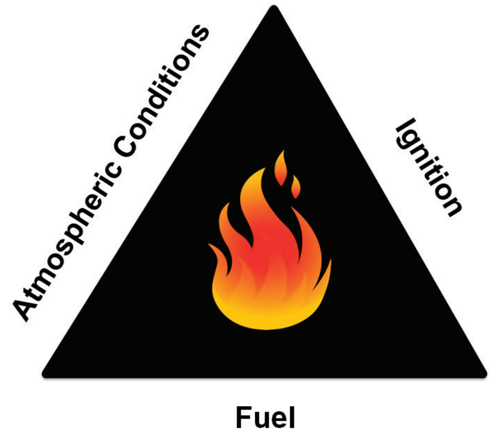


FIGURE 4-6 Components of fire.
SOURCE: Allen, slide 3.

the last 20 years. There are debates and ongoing research about how much stress and insect pressure actually changes fire hazard and fire behavior, but regardless, millions of hectares in western North America are facing these conditions. Similar circumstances exist for forests on the global scale.

Key environmental drivers of ignition are the cause (lightning or human), the quantity, the location, and the timing or season. Allen reiterated Balch's point of the number of human-ignited fires and the predominance of human ignitions in the eastern United States.

There are many different factors that influence these environmental drivers. Some drivers are changing for natural reasons—such as natural variability in the atmosphere and successional changes in forests—and for anthropogenic reasons—such as land-use change and greenhouse gas emissions. The manifestations of these changes are increases in frequency of fires, changes in area burned, a lengthening of the fire season, and an increase in fire severity. Allen provided an anecdote about changes in fire severity. On a Sunday afternoon with high wind in a forest that was closed to the public to try to reduce human-ignited fires, an aspen tree fell on a power line and ignited, which started the Las Conchas fire in New Mexico. In less than an hour, there were 150-meter (500-foot) flames (Figure 4-7A). Within 14 hours, the fire had burned 17,000 hectares (43,000 acres). It burned from high-energy, high-density fuels and immolated an area further down the slope (Figure 4-7B). The destruction caused by the Las Conchas fire demonstrates why fire-severity metrics is an area of important research today.

Watersheds and vegetation are also affected by fire severity. Areas denuded by fire can become prone to flooding and erosion. With regard to vegetation, an area of active research today is what grows back on the land after conifer seed sources are removed. Many conifer tree species that are adapted to higher frequency regimes need mother trees to survive, but these mother trees are being eliminated over large areas by high-severity fire. In such places, resprouting plants such as shrubs and grasses are favored in the ecosystem over the conifers.

Changes in fire activity affect human communities. Allen reiterated the extent of the wildland–urban interface, particularly in the eastern United States. There is a great deal of human-ignited fire in the East, but generally the East has moister conditions than the West, so the above-ground biomass is not as available for burning as it would be under western conditions. However, if and when the time comes that the above-ground biomass (or fuel) becomes more available during more of the year (that is, if drier conditions occur in the

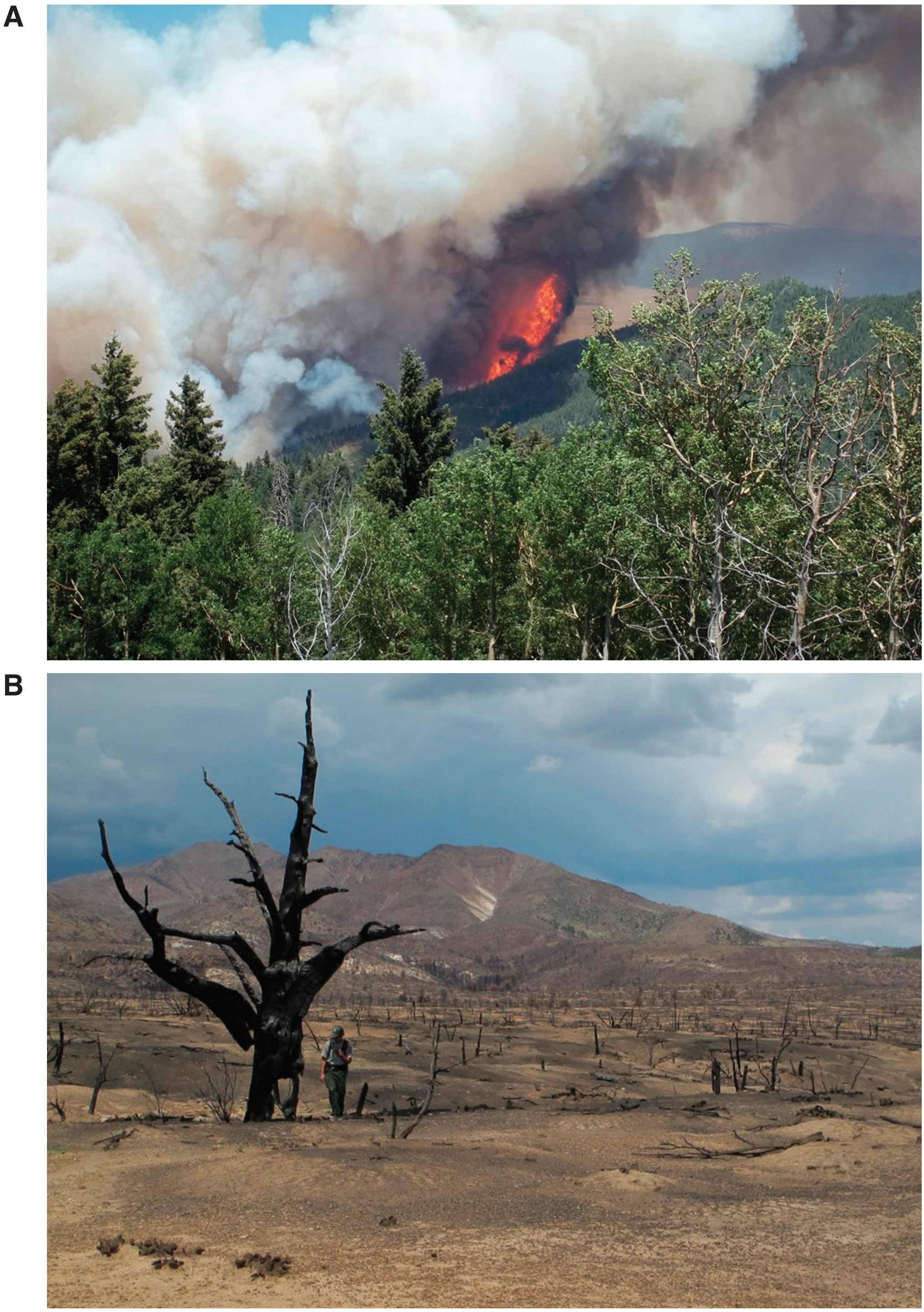


FIGURE 4-7 The Las Conchas fire, Santa Fe National Forest, New Mexico, 2011. A, 150-meter flames 1 hour after ignition, June 26. B, Landscape following fire, August.
SOURCE: Allen, slides 22, 25. Photo A courtesy of Jeff Dube, U.S. Forest Service. Photo B courtesy of Craig D. Allen, U.S. Geological Survey.

East), the potential will increase for more fire events like the one in Gatlinburg, Tennessee, in 2016. Indeed, the likelihood of such scenarios is actually quite large under a number of climate change models.

Allen said while many people have been surprised at the increase in frequency of fires and in the area burned in the West, those forests have been responding as they must. They are changing in response to the environmental drivers. As environmental drivers change, tipping-point events will become more common in the future and will occur in places they have not before, such as in a (drier, hotter) eastern United States.

Historic range of variability concepts have been used to drive management the last few decades. However, Allen supported Pyne's statement that an inflection point may have been passed; concepts based on historic range may not be useful as tipping points become more common. Instead, management will need to anticipate and adapt to an uncertain future range of variability. This shift will require a great deal of learning by scientists, managers, and society at large. For example, what will follow these tipping points that are so far outside the historic range of variability? The Las Conchas fire is an example of this, too. Five growing seasons after the fire, the ecosystem is not similar to its pre-fire state and is outside its historic range of variability (Figure 4-8).

In closing, Allen laid out a number of research priorities. The first is to learn more about nonlinear responses to systems following fires. It will be important to determine the thresholds and tipping points for environmental drivers of large fires and fast fires and the ecosystem changes that accompany them. These changes are embedded in physical, biological, and ecological processes and in human societies. Temperature-sensitive processes need particular attention because they will be the most robust climate driver in the future. Another research priority, one that is associated with nonlinear responses, is the need to better understand how extreme climate events, such as drought and heat waves, operate as triggers of tipping-point disturbance processes. A third area of research is to understand the interactions and feedbacks of these disturbances across spatial scales. All these priorities relate to a paper that was forthcoming at the time of the workshop by USGS scientists on anticipatory natural resource management in a dynamic future (Bradford et al., 2017). Such a management approach is one of the future challenges USGS is currently undertaking.

FIRE AND FUELS MANAGEMENT: WHAT WORKS WHERE?

Scott Stephens, University of California, Berkeley

Stephens started his presentation with the idea of fire regimes. Some forests are adapted to high-severity, infrequent fire—for example, crown fires in Rocky Mountain lodgepole pine—while other forests are adapted to frequent fire and can handle these disturbances within a desired range. The type of fire regime needs to be considered when fuel treatments are undertaken. Prescribed burning and thinning might be carried out at regular intervals in a crown fire ecosystem for infrastructure purposes, but such treatments are outside the ecology of that fire regime.

An example of a crown fire system that has burned too frequently is a predominantly jack-pine forest in the Northwest Territories, Canada. Jack pine is a closed-coned, serotinous species that burns every 70 to 150 years. However, in Wood Buffalo National Park, jack pine burned in 2004 and then burned again in 2014. Because jack-pine seedlings establish quickly and grow rapidly after a fire, the second fire destroyed many young trees that had sprouted after the first fire but had not yet reached maturity. There were few seeds left over in the seedbank after the second fire for another round of seedlings to generate.

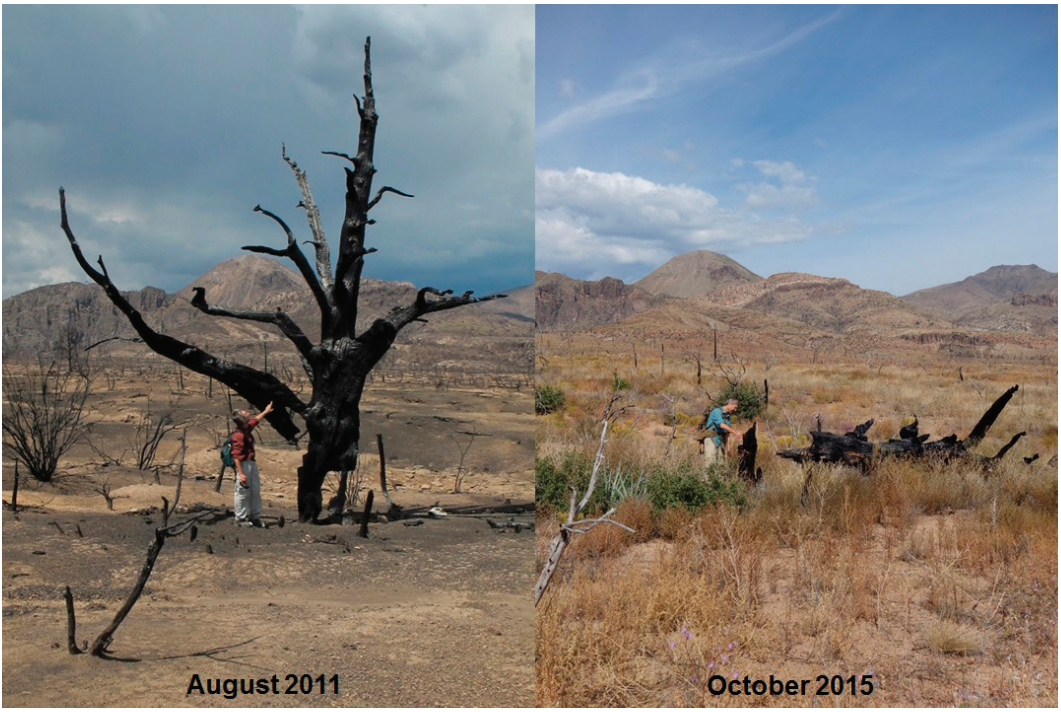


FIGURE 4-8 Site affected by the Las Conchas fire, immediately following the burn and five growing seasons later.
NOTE: The vegetation that has reoccupied the burned area is outside the historic range of variability. Woody plants used to dominate the site, but they are not thriving post-fire.
SOURCE: Allen, slide 37. Photos courtesy of Collin Haffey, U.S. Geological Survey.

Transect surveys following the second fire found one seedling in an area of almost 50 square meters. This elimination of the seed stock is an example of major vegetation changes over a short amount of time and of the abrupt changes to the fire regime that climate warming causes.

Another example of fire regime change is evident from historical data in the central Sierra Nevada in California. In 1911, there were 19 trees per acre in an inventoried area that included parts of the Stanislaus National Forest and Yosemite National Park; in 2013, the density had increased to 224 trees per acre (Collins et al., 2015). While Stephens noted that the 1911 data should not be considered a target point for restoration, he posited that the difference in the density of the forest in 1911 versus 2013 can help with understanding resilient systems.

In regimes adapted to frequent fire, the Southeast region has been a leader in the United States in the use of fire on the landscape, due in no small part to the research of H. H. Chapman, H. L. Stoddard, and E. V. Komarek. Approximately 75 percent of prescribed burning in the United States each year takes place in this region, and burning is culturally acceptable. Stephens hoped that such burning practices will continue even as people who are less familiar with prescribed fire move into the region.

There were many notable scientists at the Forest Service, the National Park Service, and universities who contributed to early research into fire and fuels, but Stephens focused on one scientist of note from the Bureau of Indian Affairs. Harold Weaver performed extensive research on the use of fire in management in the middle of the 20th century. With small crews, he burned 277,000 hectares (684,890 acres) of ponderosa pine forest in the Colville Reservation in eastern Washington between 1945 and 1955. He found that prescribed fires reduced wildfire damage by 87 percent and reduced the cost of fire control by 54 percent as compared to adjacent areas that had not been burned (Weaver, 1957). His conclusion was "this is a presentation of a management system—not just prescribed burning" (Weaver, 1957). Unfortunately, after Weaver retired, institutional support did not continue for this burning program, and it was not widely adopted elsewhere.

However, one place that did pursue Weaver's ideas is the San Carlos Apache Reservation in Arizona. During his career, Weaver had also worked in this region and supported the use of prescribed fires in its low-intensity, high-frequency fire regime. Today research is under way on the reservation on alternative fire suppression strategies. Stephens thought the outcomes of this current research will help inform how to better manage fire. Unlike the program in Washington, the San Carlos Apache Reservation program had continual institution support following Weaver's departure.

Figure 4-9 shows the response of a site in the central Sierra Nevada to prescribed burning, while Figure 4-10 displays the response of a different site in the same area to mechanical thinning followed by prescribed burning. In both series of images, shrub response is evident a few years after treatment (Figures 4-9C and 4-10C). Thirteen years after the initial treatment, the shrubs have grown larger (Figures 4-9D and 4-10D). These responses show that management is a constant conversation with a land. Prescribed burning management has to be done continually rather than as a one-time occurrence.

Experiments involving fuel treatment demonstrate that, if ladder fuels and surface fuels can be reduced, fire hazards and fire effects can be lessened in frequent-fire adapted forests. Treatments can increase the vigor, resistance, and resilience of remaining trees to adapt to climate change. Research results also have found that there are few unintended negative ecological consequences from these fuel treatments (Stephens et al., 2012). The longevity of the treatments can span 5–25 years because response and efficacy depend on the system. In some places, lightning-ignited fire can be incorporated into a treatment plan, which is the case in Region 3 of the Forest Service.[2] Research by Safford and colleagues and Martinson and Omi has determined that fuel treatments in frequent-fire adapted forests are effective when those forests are later burned by wildfires (Safford et al., 2012; Martinson and Omi, 2013); however, the use of fuel treatment is low compared to the area in need of treatment.

Lightning-ignited fires as a management tool have been used in Yosemite National Park since 1974. Collins and colleagues have shown that, when a fire intersected an area that had burned 9 years previously or earlier, the fire went out on its own in 90 percent of the cases examined (Collins and Stephens, 2007; Collins et al., 2009). Figure 4-11 is an image of one of these locations, in which lightning-ignited fire has created openings in the landscape and an opportunity for forest recovery. Figure 4-12 shows maps of the same area in 1969 and 2012. In 1969, fire had been suppressed on the land for almost 100 years (Figure 4-12A). Fire returned to the landscape in 1974 and after 40 years of using lightning-ignited fire as a management tool, there has been an increase in wet meadows, dry meadows, and shrublands and a decrease in forested area (Figure 4-12B). Compared to three watersheds where fire was suppressed, fewer trees have been killed by beetles during droughts in

[2]Region 3 encompasses 8.3 million hectares (20.6 million acres) of land in Arizona, New Mexico, and the panhandles of Texas and Oklahoma.

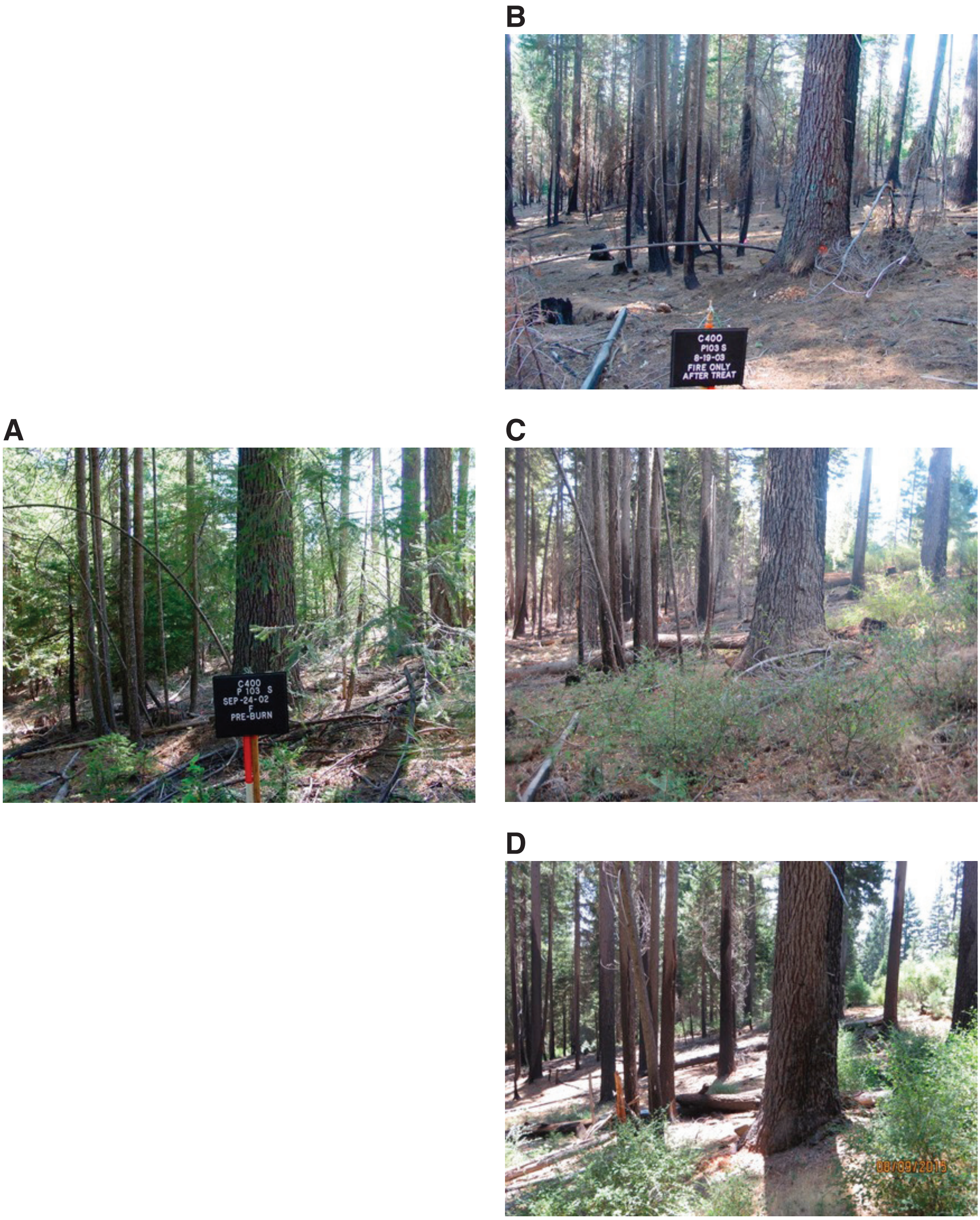


FIGURE 4-9 Study site of mixed conifer forest in the University of California, Berkeley, Blodgett Forest in the northern Sierra Nevada.
NOTE: A, site in 2002, before treatment. B, site in 2003, after a prescribed fire. C, site in 2008, just before a second prescribed fire. D, site in 2016 after second prescribed fire.
SOURCE: Stephens, slide 7. Photos courtesy of Scott Stephens.

FIGURE 4-10 Study site in the University of California, Berkeley, Blodgett Forest in the northern Sierra Nevada.
NOTE: A, site in 2002, before treatment. B, site in 2003, after mechanical thinning followed by a prescribed fire. C, site in 2008. D, site in 2016.
SOURCE: Stephens, slide 7. Photos courtesy of Scott Stephens.

FIGURE 4-11 Forest managed with mixed severity lightning-ignited fire in the Illilouette Creek basin in Yosemite National Park.
NOTE: In the foreground, the forest has been changed to grassland. The forest in the background is regenerating.
SOURCE: Stephens, slide 10. Photo courtesy of Scott Stephens.

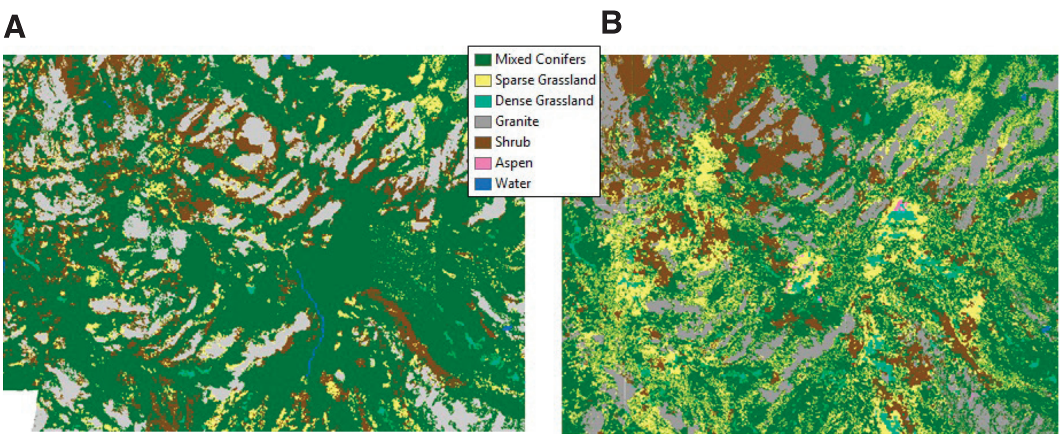


FIGURE 4-12 Vegetation change from fire use in the Illilouette Creek basin in Yosemite National Park.
NOTE: A, study site in 1969, after 100 years of fire suppression. B, study site in 2012, after more than 40 years of lightning-ignited fire used as a management tool. Wet and dry meadows have increased 200 percent compared to 1969, and shrublands have increased 30 percent; forested area has decreased by 22 percent.
SOURCE: Stephens, slide 11; adapted from Boisramé et al., 2016.

the area managed with fire and stream water volume has been stable or increased. In areas with fire suppression, stream water volume has decreased since 1974.

In conclusion, Stephens acknowledged that frequent-fire adapted forests have changed greatly in the western United States. Though climate change has made the situation worse, it is not the main problem. Fuel treatment is needed, and in frequent-fire adapted systems, it is an option. The use of managed wildfire or prescribed fire can reduce stress on the system, increase tree resilience to stress, and facilitate adaptation of the system to climate change. Crown fire systems, which rely on infrequent, high-severity fires, have fewer management options available. Prescribed burning will not be used in these systems. Stephens noted that in some such systems in Australia, land managers are reseeding burned areas via airplanes because the systems are burning too frequently for the vegetation to re-establish after a fire. Such intervention is one management option. Another option is to let the vegetation on the land change in response to the frequent fires. Which approach to take is a difficult decision.

Some resources that would help address such difficult choices are land management funding that is not linked to fire suppression, longer employment for seasonal workers so they can use fire more on the landscape, and strategies for using lightning-ignited fire as a management tool more often throughout the country (Stephens et al., 2016). Stephens said forest resilience should be a standalone land management priority for the United States. Akin to the Clean Water Act, the Endangered Species Act, and the Clean Air Act, there should be a Forest Resiliency Act. The existing acts have the power to shape policy. Such ability is needed for forests, particularly as the next 3 decades are critical for reversing the current trajectory of forest resilience. Now is the opportune time for the Forest Service and the National Park Service to set a policy that leaves a legacy of better fire and forest management for the next generation.

MODERATED DISCUSSION

A participant noted that he is stationed in Sequoia National Park in California, which instituted prescribed burning in the early 1960s and burns about 2,000 hectares (5,000 acres) a year. The primary limitation of burning is air-quality concerns. Given the size of the park and the constraints posed by air quality, it is not possible to conduct enough prescribed burning to return historical fire regimes to that landscape. He asked the panel what the solution would be to this dilemma. Scott Stephens acknowledged that the parks in the Sierra Nevada are some of those leading the way in using fire on the landscape, but over the last 20 years, the use of burning has decreased. He suggested that the best course of action is to be strategic by prioritizing important areas for management, such as giant sequoia groves. Stephens thought managed lightning-ignited fire will have to be a larger piece of the equation when it comes to using burning as a management tool. With regard to the Clean Air Act requirement that Class 1 airsheds never have impeded visibility and the public health reasons in the act for limiting smoke, Stephens admitted that there is no way to have a fire-sustainable future without smoke in the air. From his point of view, this dilemma is why a congressional act prioritizing forest resilience is needed as a prime objective of federal policy; such an act may need to supersede other policies, including those carried out under the Endangered Species Act, the Clean Water Act, and the Clean Air Act, to ensure the long-term viability of forest ecosystems. The questioner responded that the park managers are often prevented from using lightning-ignited fires as a substitute for prescribed burning because the Air Quality Board requires the fires to be extinguished if they are a threat to air quality. Stephens acknowledged this was the case and said that approach needs to change. In his opinion, federal leadership by Congress and the administration needs to revise the policy to help improve forest sustainability.

Another participant noted that two dominant themes of the panel's presentations and the keynote addresses were the uncertainty of future fire regimes and the difficulty or even inability to direct change in those regimes. The concept of resilience was also discussed, and the participant wondered what the metric for resiliency was when considering forest management in the future. Krawchuk agreed that the idea of what is defined as resilience is interesting. The theory of resilience first emerged in the 1970s, but at that time the specter of changing climate was not on the horizon. The theory put forward the idea that a system should have the capacity to absorb disturbances or shocks and retain the same state, function, and feedbacks within the same basin of attraction as it had before the disturbance. That idea of resilience corresponds to historic ranges of variability in fire regimes, climate and species, and structures of ecosystems. However, the present trajectory of change in climate suggests that the future range of variability may make the historic basin of attraction irrelevant. Therefore, there are ongoing discussions to update the idea of and the definition of resilience. The former definition of resilience needs to be put in the category of a basic resilience, and another layer needs to be added to capture adaptive resilience: that is, the resilient component is actually the capacity to transform and adapt under pressures that are novel and extreme, such as the stressors happening under climate change. Adaptive resilience, which embraces transformations and the potential to adapt by changing ecosystem state and species, is an applicable concept to forest management in the future.

Allen agreed with Krawchuk and said that the challenges for a land manager are those abrupt transformations of the system where it changes from something familiar to something novel with no legacy point of reference. Ecosystems are already adaptively responding, and it is up to managers and researchers to make sure that the systems can respond more incrementally rather than abruptly. Krawchuk added that patience is needed because, even though abrupt changes are being seen, the window of observed time is relatively small. The adaptive capacities of systems are not always known and need to be explored. The question needs to be asked whether that long-term recovery is natural or has precedent or whether the abrupt transformation leads to a different state or function. Turner noted that, because trees take a long time to grow and because fires are infrequent events (though becoming more frequent), there needs to be more empirical, observational studies or monitoring of the mechanisms that underpin the ability of the forest to recover, such as tree density, tree area, carbon, and ability to produce water. The results of those studies then need to be fed into models that can help anticipate the ranges of uncertainties and assess what those uncertainties are. This multipronged approach will contribute substantially toward understanding resilience.

A participant observed that the physics and ecology of fire science and management had been discussed, but the human dimension had not been raised. Humans are the problem and the solution. To ensure the sustainability of the system, should the human dimension be explored further to complement the work being done in the physical and ecological systems? Turner noted that the second panel had a social-science emphasis because the participant's point was so important; the first panel had a natural-science focus. Stephens shared that he was optimistic because forests and their ecosystems are so important to humans. He agreed that the social and political issues were critical when it comes to forest resilience. Land managers, including the Forest Service and National Park Service, are trying to help forests become more resilient and they need to be empowered to continue to find solutions.

A viewer of the webcast asked Finney about the use of remote sensing in forest and fire management. Finney said that there are tremendous technological tools that are able to remotely measure different vegetation and fuel attributes. However, much of that information cannot be used to make active predictions because most models cannot ingest the data. Those models that can ingest the data are too slow for real-time predictions and can only be used for research. Nevertheless, these technologies are going to continue to advance. It is incumbent upon the fire behavior sciences to figure out how fire spreads so remote-sensing data can be used and more accurate tools can be developed for the many dimensions of fire management, including mitigation. This knowledge would help close the gap in understanding with regard to how fuels are related to fire behavior. Right now fuel models act as surrogates for real fuel descriptions. The models can inform firefighters and frontline personnel about how fire behaves and how their observations actually have physical meaning about things that could be dangerous or could be opportunities for suppression. However, the predictive ability of the models for these purposes is limited. If the predictive ability of the models could be improved by having a better understanding of the physics of fire, then other sources of error could be addressed. Such improvements in the predictive capabilities of models may in turn make people more comfortable living with fire and thereby make the use of fire easier in the different ways discussed in the panel's presentations. If science is the means by which people can become more comfortable with fire as an ecological process, that would be a positive outcome, Finney concluded.

Another viewer of the webcast asked Allen about negative feedback loops. If there is more fire in a hotter, drier climate, presumably there will be no more fuel to burn eventually in some of these ecosystems. Allen said that modelers are looking at those feedbacks. However, the source of fuels changes, and there will continue to be fuels on the land for a long time, particularly in frequent-fire adapted systems where fire suppression has allowed woody fuel to build up for a century or more. Nonetheless, at some point in time, even these systems will experience some self-limiting characteristics related to fuel.

The director of the National Academies' Board on Atmospheric Sciences and Climate (BASC) shared with the panel that BASC is turning its attention to how to move carbon out of the atmosphere and store it in natural ecosystems or geological formations. Much of the conversation at the workshop had focused on more frequent fire and more intentional burning, which of course release carbon into the air. The BASC director asked if the fire community is thinking about forest systems' potential as places to store more carbon in the future. Krawchuk gave an initial response by returning to the idea of frequent fire in dry forests. When fire is frequent in these dry forests, a relatively small amount of carbon is burned off. Following the fire, photosynthesis takes hold and brings that carbon back into the terrestrial system. This pattern has no real net loss. However, fire exclusion and suppression in these dry forests has led to the establishment of ladder fuels that carry fire from the surface up into the canopies, which may result in more severe crown fires that consume whole trees and lose more biomass. Growth may not be able to regenerate following such intense fires, and this situation can create the potential for less uptake by large trees (which act as big carbon-sequestering devices) of those carbon pools due to reduced photosynthesis. Therefore, more frequent fire would avoid those tipping points that release large amounts of carbon. Even though there is a flux of carbon sequestration and release in a frequent fire system, there is not necessarily a huge release of carbon. An exception would be tundra fire that burns down into long-established pools of carbon, but that is a different kind of system from the crown fires of the West.

Stephens added that Matt Hurteau of the University of New Mexico and Malcolm North of the Forest Service have looked at the sustainable carbon carrying capacity of a forest. The fire regime is really important to that capacity. For example, coastal forests of the Pacific Northwest, which are comprised of species like Douglas fir, western red cedar, and redwood, experience few fires and can sequester a great deal of carbon. In fire-prone areas like the Sierra Nevada, above-ground carbon stocks have historically been low. In the 1911 data from the California Sierra Nevada that Stephens cited in his presentation, the amount of carbon per hectare was approximately 100 megagrams. That is a very low number compared to the carbon stocks of today's California Sierra Nevada mixed conifer forest. High carbon stocks will not work in a frequent-fire adapted ecosystem and will lead to tipping points, to which Krawchuk alluded. Carbon in forests is important, but the historical range of a regime's ability to hold and sequester it needs to be considered. The ability of most of the areas of the western United States to hold carbon is probably lower than the amount of carbon that is being held in these regimes today. Continuing to hold the carbon stocks of today in western forests will not be sustainable, in Stephens' view.

A participant in the audience said that, with the climate changing and fuel building up over the last century, more fire in the foreseeable future is guaranteed. While more fire on the landscape is needed, prescribed crown fires are nearly impossible to conduct. Therefore, managers are dependent on acts of God to set crown fires in places where they are needed. In the view of the participant, it is irrational to wait for fires to occur because they may start at the wrong time when, instead, fires could be set at the right time, even though sometimes unintended negative consequences will occur. Setting such fires obviously has a social, human dimension, but it also has a modeling dimension. One of the challenges to pursuing such actions that the participant heard in the panel discussion was uncertainty in modeling. He asked Finney if he could expand on what the missing pieces in modeling are that would enable more accurate modeling of fire spread.

Finney responded first that crown fires are not impossible to ignite for prescribed-burning purposes. This approach is used in the Northern Rocky Mountains, and the Canadians are experts at starting such fires with the use of helicopters. The proscription against these kinds of burns is sociopolitical and cultural; technically, they can be performed successfully.

With regard to the modeling, Finney said there are many fine-scale physical unknowns. For example, how long do fuels burn? What is the burning rate of a given fuel complex? How do fuels ignite? How does slope affect wildland fire spread? Are the effects of slope different from those of wind? Finney said there is good evidence that slope and wind have different effects but that the difference is not well understood. The coefficients of the two are currently applied algebraically without a real physical explanation.

A bigger question relevant to modeling for which the answer is unknown is: Are large fires different than larger small fires? They appear to be because they have different characteristics at a macro-scale that make them partly an atmospheric phenomenon. The burning rate probably changes and is not just a function of the physical layout of the fuels and their loading by size class.

Therefore, Finney concluded, there are dozens of fundamental questions that need to be asked and answered in order to build reliable physical representations of those questions and answers in models. Without this understanding, opportunities are being missed to have simple physical models that are fast and reliable. Whether the inputs can be gathered to model precisely the answers to such questions is yet another question. However, with the advance of technology, it certainly seems that input-gathering is not a current limitation.

5

Living with Fire: State of the Science around Fire-Adapted Communities

The second panel turned the attention of the workshop participants to the social-science research on living with fire. The four presentations were followed by a discussion session moderated by planning committee member Jeffrey Rubin.

UNDERSTANDING THE WILDFIRE POLICY CONTEXT: WHERE ARE WE NOW?

Toddi A. Steelman, University of Saskatchewan

Steelman began by saying that she prepared her presentation from the perspective of what a line officer in the Forest Service needs to know in order to work effectively the 2017 fire season and for future fire seasons. The main framing question is: What kind of decision space will line officers have under the current presidential administration and Congress to accomplish their given goals? Steelman took the goals of the National Cohesive Wildland Fire Management Strategy as given because there is good understanding of and agreement on them. They are

- Restore fire-adapted ecosystems,
- Build fire-adapted communities, and
- Respond appropriately to wildfire.

As was established in earlier presentations, the current problem is larger and more intense wildfire, and the challenge of managing it is in part due to climate change. Larger, more intense fires are being seen in North and South America, including in places where they are not expected (for example, the November 2016 fire in Gatlinburg, Tennessee). The system leading to these fires is complex, and a framework is needed to understand some of that complexity.

Complexity occurs at temporal and spatial scales. Spatial complexity is occurring at the global, national, regional, and local scales, and those different scales interact with one another. Temporally, complexity takes place within seasons, decades, and centuries. Filling in some of the events and conditions that occur on these spatial and temporal scales begins to flesh out an integrative framework of how wildland fire science can be understood (Figure 5-1). It brings together some of the social, biophysical, and engineering sciences to lend greater understanding to complexity involved in the whole system. For example, at a global or a national level, the interplay of social and ecological components is apparent in climate change, wildland fire regimes, and fire intensity as well as in how climate change policy begins to be a response to those three components. At the national and regional scales, the social and ecological interplay is evident via landscape-scale vegetation changes, fire severity, shifts in species structure, and conflicts between state and federal budgets. The wildland–urban interface (WUI) and how it has developed over the past several decades to create the problems that are currently being experienced is another component through which the complexity of social and ecological interplay can be observed and understood. Finally, all these components come to bear at the local scale, where the line officer has to deal with everything from fuel loading and weather to several large fires each season, evacuees, death, and destroyed structures. Funding issues for fire suppression and funds diverted from other management priorities to fire suppression are socioeconomic pieces that come into play at the local scale.

Viewing the problem through this framework requires thinking in a more anticipatory way. What would anticipatory governance and anticipatory management of wildland fire look like today and into the future? That is, what can be expected related to wildland fire in the next several years? As previously stated, it is expected that climate change and large fires are going to persist. Steelman also expected that, under the Trump administration, little action on climate change would be taken at the national or international scale. Therefore, decision space should not be devoted to thinking about solutions related to national or international climate change action. Similarly, the budget blueprint released by the Trump administration on March 16, 2017, called for a $53 billion cut in discretionary spending, which will affect the U.S. Department of Agriculture, the U.S. Department of the Interior, the U.S. Environmental Protection Agency, and the Federal Emergency Management Agency

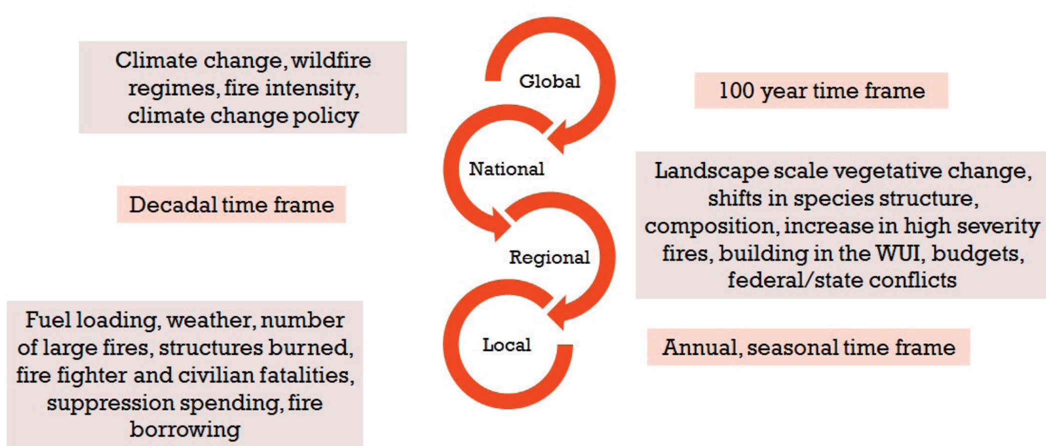


FIGURE 5-1 The interplay of social and ecological components in wildland fire management across time and space.
SOURCE: Steelman, slide 5.

within in the U.S. Department of Homeland Security. If such cuts are enacted, they will have consequences for fire management in the upcoming years. Because the budget had not yet been approved by Congress, Steelman said there would be some decision space to establish some priorities until the budget's finalization in October 2017.

There will also be increased pressure on state and local budgets. State budgets will be particularly affected by health care spending requirements and infrastructure needs. At the local level, the expiration in 2015 of the Secure Rural Schools and Community Self-Determination Act means that 700 rural counties with national forest land received the last transfer of federal funding for public schools, roads, and other municipal needs authorized under that act in the fall of 2016. Competing priorities and declining funds will have consequences for how wildland fire is managed at the local level.

How are line officers going to manage forests under these leaner fiscal conditions and environmental and social complexities? Where is the fire science and management community going to find the decision space to meet the goals of restoring fire-adapted ecosystems, building fire-adapted communities, and responding appropriately to wildfire?

With regard to the first goal, the fire science and management community can look to some existing projects that are increasing the pace of restoration at the regional scale. Steelman gave three examples of such projects: the Forest Resiliency Project of the Blue Mountains Restoration Strategy Team in Oregon and Washington,[1] the Four Forest Restoration Initiative in Arizona,[2] and the From Forests to Faucets collaboration between the Forest Service and Denver Water.[3] Congressional delegations need to be made aware of the importance of working at this regional scale over the timeframe of a decade. If progress is not made regionally over this period of time, no progress will be made at the local scale.

To build fire-adapted communities, more collaboration is needed within the WUI. Line officers do not have much power when it comes to dealing with private land, but they do have Community Wildfire Protection Plans and Good Neighbor Agreements. Steelman thought authorization for these types of collaborative approaches would be politically appealing to the 115th Congress. Line officers and people at the local level also have stewardship contracting available as a tool.

To meet the goal of responding appropriately to wildland fire, line officers seek to lose as few lives as possible to fire, protect values at risk, and manage risk appropriately. An option for meeting this goal is to coordinate a wildland response network, which brings together local-level entities—including fire and disaster management officials, local government representatives, and the media—before a wildland fire happens so they can perform effectively and collaboratively during a fire. Too often fire management is thought about as only federal, state, and local fire services, but effective management actually requires much broader participation for frontline action, particularly when trying to manage something like a big box burn. A big box burn may be an opportunity to put more fire back on the landscape if a fire happens on a national forest, but it cannot be done effectively if a network of local entities has not been established before that fire.

In conclusion, Steelman said that there is a framework to think about spatial and temporal complexity. When thinking strategically and tactically about the complexity that exists for line officers in national forests, three areas within this framework where Steelman

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[1]Blue Mountains Forest Resiliency Project. Available at https://www.fs.usda.gov/detail/r6/landmanagement/resourcemanagement/?cid=stelprd3852678. Accessed July 3, 2017.

[2]The Four Forest Restoration Initiative. Available at https://www.fs.usda.gov/4fri. Accessed July 3, 2017.

[3]From Forests to Faucets partnership renewed and expanded. Available at http://csfs.colostate.edu/2017/02/28/forests-faucets-partnership-renewed-expanded/. Accessed July 3, 2017.

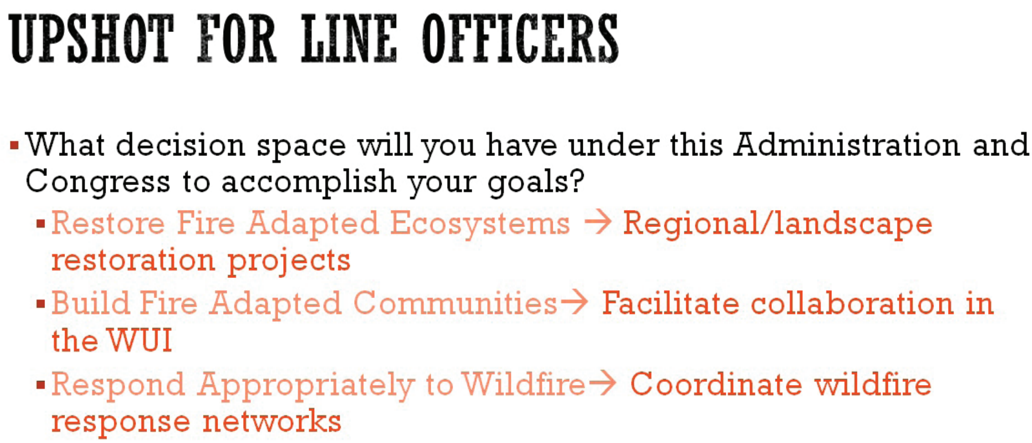

FIGURE 5-2 Areas with decision space in the current wildland policy context.
SOURCE: Steelman, slide 12.

thought action could be taken in the coming years are: (1) regional/landscape restoration projects, (2) coordinated wildfire response networks, and (3) collaboration in the WUI (Figure 5-2).

FACILITATING ADAPTATION: COMMUNITY VARIATION IN THEIR RELATIONSHIP WITH AND RESPONSE TO WILDLAND FIRE

Travis Paveglio, University of Idaho

Paveglio's presentation focused on social diversity in the WUI. Fire can occur in a variety of places, but Paveglio pointed out that there is a tremendous amount of social diversity in places affected by fire, and that diversity is often overlooked. Additionally, the people living in areas affected by fire are changing. They may have different abilities or perspectives about how they can work with land managers, agencies, or nongovernmental organizations to successfully live with fire.

His overarching point was there is no one way to live with fire. In a number of studies across the western United States, it has been observed that people will have to adapt in different ways. People living in communities that need to adapt to fire first need to be understood before science can be tailored in a way that fosters an agreed-upon approach within the community to living with fire. Otherwise, interventions will be ineffective.

Paveglio's work has concentrated on understanding and characterizing the social diversity in communities living with fire. What does that social diversity mean when people may have differing abilities to reduce fuels on their properties or when they may have different capabilities for writing grants to get money for fire management or adaptation activities? How does that social diversity affect whether they stay and defend their properties, as they often do in many of the places that he has studied? There is a tendency in social sciences on wildfire to see "the public" as one singular entity, but it usually is not. There are many diverse views and communities within "the public"; therefore, the unit to address when tailoring messages is the one in which change can be achieved. Paveglio's research group defines the unit (community) as people who will come together, care about an area, and propose and carry out some type of action. The unit size can vary, and it can fragment over time as a landscape changes. For example, a community could be timber dependent or range dependent, but over time those activities could decrease and in their stead, more people could move in, creating smaller communities that do not interact in the way the timber or range dependent community did.

To understand this social diversity and the ability of social structures of communities to change, Paveglio designed a framework of characteristics to represent diversity in a given place (Paveglio et al., 2009). Demographic and structural characteristics—for example, peoples' income levels, their willingness to pay, and how old they are—are often examined because data exist for those types of diversity. Those characteristics are important, but they do not capture other components of social diversity, such as

- The ability of a unit (community) to access and adapt scientific and technical knowledge to local circumstances,
- The ability of people to work together in effective networks, and
- The place-based knowledge and experience held within the unit, including traditional ecological knowledge that encompasses a long-term understanding of burning in those places.

Paveglio and Edgeley (2017) have developed 22 characteristics that nest within this framework. Together they create a corpus of characteristics that managers can use to go to any community living with fire and ask, "Which of these characteristics intersect and how does the intersection lead to different types of adaptation within the community?" The characteristics of social diversity might not always intersect in a way that facilitates adaptive capacity. In such a case, adaptive capacity development might need to be undertaken, which is why is it important to understand the capability of the community first before conducting additional science because people may not use modeling outputs the same way or they may not use the same types of fire-wise programs.

An analysis of 20 years of case studies has identified four different archetype communities across the western United States (Figure 5-3). Formalized suburban communities are those that tend to be small in area, such as a gated community or a community with a homeowners' association, in which standards for maintaining space free of fuels around a home or structure could be created. High-amenity/high-resource communities are those that have more people with second homes. People in these communities may be more inclined to focus on fuels reduction for landscape health or on actions that will sustain recreation opportunities. Rural lifestyle communities often have diffuse patterns, and people in these communities may be more interested in privacy. A difficulty in conducting prescribed burns or creating collective fuel breaks in these types of communities is that they often want to have wildlife habitat or traditional activities, like hunting, near their homes. Working land-

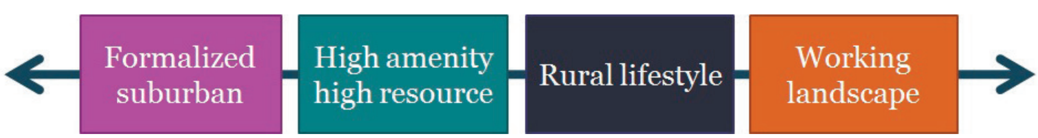

FIGURE 5-3 Spectrum of archetypal communities in the western United States.
SOURCE: Paveglio, slide 4.

scape communities have people who have a tremendous amount of local knowledge and who probably have fought fire themselves. Their knowledge can be utilized; this has been seen in some studies with range and fire protection associations, where ranchers have interfaced with incident commanders and provided initial fire suppression on remote public lands.

Different policies and programs will be more effective with the people in these archetype communities to help them in their adaptive capacity. The framework designed by Paveglio can be used to explain why it is that people in one type community find a certain pathway to be the most effective course for adaptation. The framework can also be used to decipher the best way to communicate messages about adaptation to them and to identify the data they need to sustain their communities. The goal is to work with a community's culture, not against it. Communities need to be able to choose their own pathways to living with fire, and they need to have the tools to characterize their conditions in order to communicate why they need to adapt the way they do. They also need to be able to work with partners, if desired, such as federal agencies or nongovernmental organizations. In some cases, communities advocate that no government involvement is necessary for them to adapt to living with fire.

Paveglio and colleagues are currently testing different policies—such as Community Wildfire Protection Plans at different scales, incentives, and matching grants—across the community archetypes to

- See how policies may be better supported in some places than others, and
- Work on co-developing the type of knowledge needed to be able to identify what types of policies will work in which types of community.

This research is needed because fire-resilient landscapes need fire-adaptive communities within them, and people are a component of the landscape that has to be understood. People are fragmenting landscapes, and their views about the way they are managing land, their attachments to a place, and the scale at which they want management (federal, regional, or local) are all changing. The social component of fire (people and the type of community) affects the fuels that end up being treated or burned (intentionally or not), the ways people respond to fire, whether or not there will be conflict after fire, and whether or not there is support and use of local knowledge in effective ways.

The framework is not just useful to scientists or fire managers. If people can self-identify with the social diversity characteristics in the framework and managers can also use them to quickly understand that context, then everyone has consistent data. For managers, this framework is a way to recognize community characteristics and a tool to identify effective strategies for working with communities that have those characteristics. It also builds from prediction to a "science of practice," in which the identification of effective strategies takes place through work with communities, rather than using existing theories or tests to prove that there is a problem.

In the end, there are no theories for community adaptation to wildfire in social science. Most of the theories that exist have been taken from psychological or social theories. Paveglio stated that he and his colleagues are trying to build a theory that allows for a quick understanding of the social diversity of communities living with fire and what it means for differential adaptation. Because policies, interventions, and management strategies are effective only if people adopt them, understanding that diversity is important. Building policies, inventions, and management strategies with the idea that they will be adopted if the community is convinced about the proposed course or educated to see the utility of the suggested adaptation will not work. In the future, Paveglio added, variable assessments will be needed to understand

- How fire-adapted communities are going to adapt differently depending on their archetype,
- What incentives, policies, and strategies will get people to respond to fire depending on their archetype, and
- How incentives, policies, and strategies can be equitably deployed across different types of communities.

These types of assessments will help information flow from communities to managers and policymakers and improve management across boundaries and across different, diverse people.

TRANSLATING FIRE SCIENCE INTO FIRE MANAGEMENT

J. Kevin Hiers, Tall Timbers Research Station & Land Conservancy

Before he was a wildland fire scientist at Tall Timbers Research Station, Hiers was a land manager at Eglin Air Force Base near Valparaiso, Florida, which has one of the nation's largest fire management programs. With his mentor James Furman, the U.S Forest Service Liaison at Eglin's Wildland Fire Center, Hiers set over 40,000 hectares (100,000 acres) of prescribed fire each year and fought an additional 100 wildfires annually. Whether a manager operates on an air force base or a national forest, it is worthwhile to step back and understand the context of a location because, wherever that location is, a policy management trap exists when it comes to fire. That trap encompasses 100 years of fire suppression and fuel accumulation as well as the growing WUI. For example, in Florida, the abundance of homes and other infrastructure built along the coast means that the WUI has become a central consideration of any plan for prescribed fire. In the West, the WUI has caused fuels treatments to become the focus of fire management actions. This attention to the WUI rather than forest or ecosystem health leads to limitations in desired landscape outcomes.

Hiers noted that adequate resources do not exist to appropriately address the United States' fire problem. Inordinate attention to the WUI exacerbates the problem because it creates the policy management trap in which fire managers put out easy fires and choose to set hard ones. These management actions mean that the capacity to appropriately treat the greater fire problem in the United States is continually diminished because of the amount of resources devoted to managing fires on the dynamic, sinuous edge of the WUI. The dearth of resources to treat the greater fire problem restricts treatments to small spatial scales, which are typically ineffective in preventing or mitigating large fires. Traditional fire science and management approaches cannot solve this wicked problem.

Hiers has spent much of his career at another interface, that is, the fire science–management interface. Fire managers are a diverse group and include prescribed burners of privately held land, federal firefighters, and state suppression agencies. The diversity represents both a challenge and an opportunity for translating science. However, all managers rely on experience to address uncertainty and to address fire behavior and fire management objectives. Because they rely on experience, trial and error are important; however, fire and prescribed burning occur today in a society that has little capacity to tolerate error, Hiers said.

Fire scientists are a diverse group as well and come from disciplines as varied as meteorology, physics, forestry, ecology, and, increasingly, the social sciences. In an attempt to be relevant, fire scientists often are tool-focused and recommendation-focused so that they can tell managers how to better manage their land. The unintended consequence is that decision space is often constrained in this increasingly complex world. When mistakes are made by quantifying the obvious rather than focusing on what managers need to know, little science is translated into management actions.

Because Hiers has spent much of his career on this border between fire science and fire management, he emphasized a few characteristics that are important barriers to overcome. First, managers rely on experience as the currency of credibility. This experiential learning is different from structured learning. The scientific community, with its incentive to publish papers, has dialogs and arguments in the peer-reviewed literature; however, that conversation does not always translate well to on-the-ground experience. Second, managers have specific circumstances to deal with—the fire of the day that has a particular set of management objectives, topography of fuels, and atmospheric conditions—whereas scientists seek generality in their world view. Generalization changes scientists' understanding of managers' risks. Third, the complexity in fire management versus the orientation of fire science around specific disciplines increases the challenge of applying science to management. For example, when a prescribed fire is set in the WUI, the manager's job is on the line and he or she has to integrate all of the different disciplines of fire science into that day's burn. As fire scientists dive deeper into the depths of particular disciplines, the ability of managers to integrate the findings of research from these different areas of expertise and apply them to a specific burn becomes more and more difficult.

A different approach is needed. First, translational fire science, which is process-oriented not tool-focused, is needed. Hiers posited that solutions to the United States' fire problem will come from long-term, shared experiences where scientists are on the fires with managers, providing the circumstances for each group to become fluent with the other. Second, fire science outcomes *must* begin to address uncertainty, he said, rather than what is already known, and focus on fires that *can* be controlled, like prescribed burns. Even for prescribed burning in the Southeast, tools are still needed to develop objectives and prescription parameters. Third, the disciplinary breadth of fire science needs to be expanded to social scientists. Many of the solutions discussed at the workshop were outside of the traditional realm of fire science expertise. Hiers commented how important it was to have social scientists present at the workshop and how their participation in fire science and management is absolutely critical. More incentives need to be provided for social scientists to participate in and contribute to solutions.

Many building blocks exist for moving toward this new approach, including prescribed fire councils, regional fire exchanges through the Joint Fire Science Program, and the Prescribed Fire Science Consortium. Hiers emphasized that when managers and scientists burn and manage fires together, they learn together. One of the premier National Interagency Prescribed Fire Training Center courses is an agency administrator course, which brings the line officers into a context where they see what managers face every day. Shared experiences like the one provided in the course are key, but such mentorship programs are lacking. Formal adoption of shared experience as a strategy has yet to occur, and agency leadership is needed to provide incentives for scientists to participate in an experiential way.

Hiers concluded with a case study at Eglin Air Force Base, where he and Furman unwittingly created opportunities for shared experience. When they arrived in the late 1990s, they found an Air Force base with 200,000 hectares (500,000 acres) of longleaf pine that needed frequent fire. The base already had a long-term commitment to relationships with researchers, primarily in the ecology and wildlife science fields. However, the existing program was wholly inadequate in its capacity to conduct prescribed burns on the scale necessary; only 13,700 hectares (34,000 acres) were being burned each year on a 200,000-hectare landscape that needed to burn every 2–3 years. To address this situation, Furman and Hiers built upon the research–management relationship that already existed and, as more research was conducted on the base, they gained site-specific solutions to some of the problems. At the same time, scientists and managers experienced fire together on the fire line, and individuals who had never been on the line were able to see what managers faced, including the practical constraints of conducting research.

This collaboration also assisted with putting in place a burn prioritization process. There was not enough capacity in the fire management program on the base to burn the target amount of area each year. Therefore, Furman and Hiers focused on the worst habitat and, rather than disaggregating fuel treatments, they worked with fire managers, fire researchers, and wildlife biologists to aggregate treatments. They hoped that by burning and maintaining the best quality habitat, the fire-dependent ecosystems in these locations would slowly grow capacity over time. Ten years later, the treatment capacity had tripled, and the goal of burning over 40,000 hectares (100,000 acres) a year is frequently met.

Regional solutions with innovative, dynamic, and robust fire management–science partnerships can play a key role in addressing the policy management fire trap. More fire is needed on the landscape, not less, and national policies will not work as well as regional policies to introduce that needed fire. Shared experience is the bridge between management and science.

ADAPTING TO WILDFIRE: MOVING BEYOND HOMEOWNER RISK PERCEPTIONS TO TAKING ACTION

Patricia Champ, U.S. Forest Service

Champ's presentation focused on how to get homeowners to take action to protect their properties from fire. She framed this challenge as a last-mile problem, which is a concept from the literature on supply chain. The last mile is the end of the supply chain where a product is transferred to the customer. The last mile is often the most difficult part of the entire supply chain, and for that reason, it should not be thought about last.

Champ used a bridge to nowhere (based on a TED talk idea by Harvard University economist Sendhil Mullainathan) as a metaphor for the last-mile problem in fire science and management. A great deal of engineering has gone into building the bridge, yet it leads nowhere. Likewise, a century's worth of fire science has been conducted, resulting in a better understanding of fire behavior and home ignitability. Yet there are still homeowners who do not take action to mitigate the risk posed to their property by fire.

Research finds that, generally, homeowners in the WUI understand that they live in a fire-prone landscape and that they are vulnerable to losing their home. However, taking action is not simple, Champ said. First, as Paveglio discussed, community context matters. Second, homeowners need specific information to take action. Therefore, the general concept of the home ignition zone (Figure 5-4) needs to be made applicable to the particular hazards on an individual homeowner's parcel, such as the trees near a wood deck. Third, multiple interactions with the homeowner are required to induce action; one message to a homeowner about defensible space will not lead to behavioral change. The homeowner needs to interact on his or her property with someone he or she trusts, such as a volunteer from the fire department, a local wildfire council member, or a state forest service representative.

To find ways to solve the last-mile problem of homeowners taking action, Champ is part of an interdisciplinary research collaboration team called Wildfire Research (WiRē), which focuses on homeowner wildfire risk mitigation and community wildfire adaptedness. WiRē serves as a model of joining research and practice. The personnel come from three different federal agencies: the Forest Service, the U.S. Geological Survey, and the Bureau

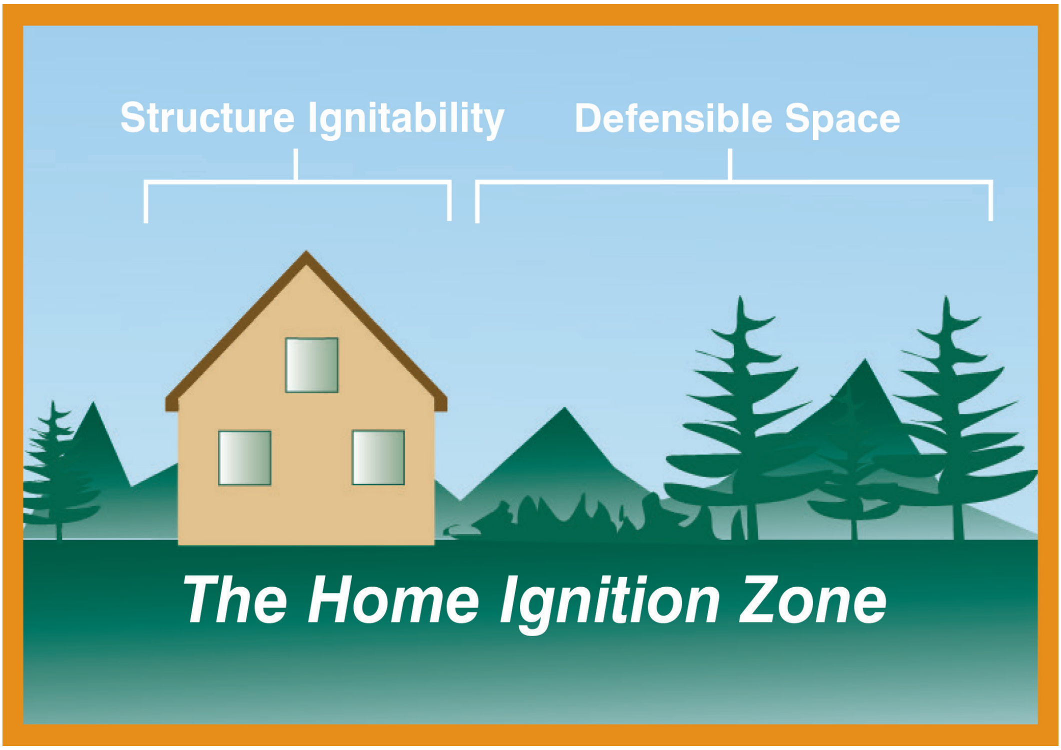

FIGURE 5-4 The home ignition zone.
SOURCE: Champ, slide 4. Image courtesy of the Colorado State Forest Service.

of Land Management. The University of Colorado, Boulder, is also a partner as are two wildfire councils in Colorado. As of early 2017, most of WiRē's work had been conducted in Colorado, but the team expected to work in other locations soon.

As of March 2017, WiRē had collected systematic data in 87 Coloradan communities. To generate the data, the practitioners conduct a rapid risk assessment for every parcel that has a structure in the community. This assessment is based on 11 attributes, such as where the parcel sits in the landscape and the vegetation on the parcel. Some of the attributes relate to the structure that is on the parcel. At the same time, the local community conducts social surveys. These surveys help WiRē learn about the people who live on the assessed parcels.

WiRē has used the collected data to understand the effectiveness of different kinds of nudges. Nudges are messaging efforts that seek to encourage behavioral change. The WiRē team designed an experiment with three nudges and ran it in a Coloradan community where homeowners had not taken mitigation measures to protect their homes. The community had a cost-share program in place for years to encourage such measures, but no one had taken advantage of it.

In each nudge in the experiment, a letter was sent out to homeowners in the community. In the first group, homeowners were told in the letter about their community level of wildfire risk. That information comes from the century of research on how to conduct risk assessment. In the second group, homeowners were told about their community level of risk and their parcel level of risk. That information builds on the pioneering work that Jack Cohen did within the Forest Service's research arm on the home ignition zone.[4] In the third group, a social norm piece was added to the letter. Homeowners were told about their community level of risk, their parcel level of risk, and the level of risk of their 10 nearest neighbors. Homeowners could respond to the letter in one of three ways: (1) they could go to a website that was individualized with risk assessment data for their parcel of land so they could see how their parcel was rated on the 11 attributes; (2) they could call the West Region Wildfire Council, the practitioner part of this venture; or (3) they could attend a community meeting.

WiRē's results had not been published at the time of the workshop, but the preliminary data suggest that response rates were good across all three groups. More importantly, when it comes to the last-mile problem, community members undertook more defensible space projects in the last 4 months of 2016 (after the letters were mailed) than they had in the 5 previous years combined. Though the absolute number of projects was small (17 as of the end of 2016), this increase was a substantial change in the community compared to the years before the nudge experiment. Champ and the rest of the WiRē team planned to follow up with homeowners in 2017.

In closing, Champ posed the question: How can a century's worth of fire science be used to help homeowners adapt and live with wildfire? One way is to unite research and practice, which might look different depending on a scientist's wheelhouse. Another way is to understand the importance of personal relationships. The relationships matter within the WiRē team; for example, Champ has been working with BLM for over 12 years. Relationships also matter when working with homeowners to build their trust and induce action. Finally, Champ reminded the audience not to think of the last mile last.

MODERATED DISCUSSION

A participant asked if messaging to the public should communicate that mechanical treatment (such as thinning) is needed along with prescribed burning and whether that message needs to be communicated at the middle mile, not just the last mile. Champ responded that often when the fire science community talks about the public, their notions of who or what the public is are not supported by data. Once the social piece has been investigated, it frequently turns out there is more support for fire on the landscape in fire-prone communities than was originally presumed or at least there may be a foothold of support that may grow with more communication from fire scientists and fire managers. However, there has been little research that looks closely at public support for fuels treatments in a specific sense, that is, fuels treatment next to a homeowner's house or in his or her community. Champ was not sure what the optimal message would be, but that messaging needs to be different depending on the place. For example, there are rural landscapes where burning is used regularly for land management; prescribed burning may not bother the people in these landscapes as it might elsewhere.

Paveglio added that the 22 characteristics in his framework aim to discover different communities' comfort level with fire on the landscape. In working landscapes, his research has found that people are generally on board with the idea of prescribed burns, but that will not be the case in all places. The tailored message would include planning for where mechanized fuel treatment should occur and where prescribed burning should be done. In another location, depending on the type of people, how they are situated, what their ownership patterns are, and whether or not they work together, a large break in vegetation across

[4]See The Jack Cohen Files. Available at http://www.firewise.org/wildfire-preparedness/wui-home-ignition-research/the-jack-cohen-files.aspx. Accessed July 3, 2017.

an area with wildland fuel might be the correct course of action, and prescribed fire might play a background role in that location. Paveglio and his colleagues are testing tailored incentives for different scenarios, with the hope to develop from this work a range of options that people can choose from to address fire issues. That data will also help researchers understand why a fire-prone community selects a particular course of action. Different approaches can be taken by communities to get to the same ends of fire adaptation, for example, Community Wildfire Protection Plans, fuel reduction, evacuation planning, and land-use planning. In the end, fire-prone communities need to learn how to live with fire; that will look different in each location.

A viewer of the webcast asked how legislation like the Endangered Species Act or the Wilderness Act affects fire management. Steelman did not anticipate that there would be much appetite in the 115th Congress or in the Trump administration to revise the Endangered Species Act. The situation with greater sage grouse—which was recently a candidate for the endangered species list—will be interesting to watch because managing for species abundance has constrained management of wildfire; however, Steelman did not think the balance of policy objectives currently in place would change in the near future. With regard to the Wilderness Act, Steelman thought that there would be less funding available to protect new areas, either under the jurisdiction of the Forest Service or the U.S. Department of the Interior. Rural communities derive benefits from having federal lands like wilderness areas near them. Ownership of those lands has been contentious in some states but less so in others, which relates to Paveglio's point that effects are differentiated depending on the community. Steelman doubted that there would be pressure to turn ownership of all the federal lands back to the states simply because it would be too expensive for the states to fight fires on these lands. Therefore, whereas such pressure existed during the Reagan administration, Steelman did not think it would resurface because the states cannot afford the management costs.

Hiers noted that, for fire management at Eglin Air Force Base and several other military installations in the Southeast, the Endangered Species Act was an extremely beneficial tool for reducing wildfire risk on those properties. Fire-dependent endangered species like the red-cockaded woodpecker had large populations on U.S. Department of Defense (DOD) land. The use of prescribed fire was a win–win proposition because it reduced wildfire risk and it managed for the habitat of those endangered species; the management approach can serve as an example for similar situations on land not managed by DOD. Paveglio added that a converse example has occurred in critical greater sage grouse habitat, where the Endangered Species Act was used to protect habitat for sage grouse that was threatened by fire. The use of such a policy tool may not always lead to a fire-resilient landscape, but it directs the actions people take. Communities have some agency[5] within the policy space to work toward an end goal however they want and to plan for that goal in ways that meet their needs.

Another participant noted that a lot of research is done on how forests and wildlands burn and on how to improve fire-management practices. However, he has heard little discussion or research about better community planning to address fire risk. What work is being done with regard to community planning, and what agency or group should be encouraging such work? Steelman offered the first response. She said Community Wildfire Protection Plans are one tool available to help communities plan for fire risk. These plans were included in the Healthy Forests Restoration Act of 2003. They are a way for the community in the

[5] In social science, *agency* is the capacity of individuals or a collective entity to act independently and to make their own free choices.

WUI to come together with the state and federal agency representatives to do comprehensive planning in that interface and prioritize areas where they would like fuel treatment as well as prioritize the values at risk that they would like protected during a large wildland fire. Having been in place for over a decade now, the benefits of those plans are starting to be seen. They demonstrate the importance of putting such types of opportunities in place at many different scales (local, regional, and national) because the desired outcomes take time to come to fruition. Another tool available is a Good Neighbor Agreement, which is a way for federal forest lands to be mechanically treated by state agencies. The state agency can conduct the environmental impact assessment and treat that area right in the WUI. The funding for this program makes it possible for treatment done on the urban side of the interface to be matched by treatment on the federal side of the property. This tandem work creates a fuel break, leading to a landscape that is more fire resilient overall.

Paveglio added that his group has conducted research in which they have taken modeling outputs and created different social vulnerability maps at the parcel level. Those maps are then matched up with some of the barriers to overcoming the last mile that Champ discussed. The result provides information about the perspectives of people in the community, how long they have lived in the area, and from whom they get their information. One of the findings of that work is that most of traditional social vulnerability indicators—both demographic and structural—were not well matched to the western communities included in their research. This mismatch shows a need to look again at how planning might be structured and how those people might set up a system in their communities to address their most important concerns. As an example with regard to values at risk, if an incident commander from out-of-state arrives at a location, he or she may be unfamiliar with the values that community may deem important. There needs to a system or set of steps in place so that when such an incident commander arrives, the community can communicate that they, for example, want to emphasize protection of the grasslands and the forest lands that they (the community) have invested in whereas structures like an old farmhouse can be deprioritized. When this process occurs, most incident commanders prioritize the values that matter to the community as long as the associated actions do not cause any harm to firefighters. Land-use planning can be done in a similar way so that community social norms are prioritized.

Craig Allen asked what is known about public acceptance of smoke from the prescribed burning in the Southeast. Hiers said that smoke clearly is a tremendous impediment to conducting prescribed fire. For example, at Eglin Air Force Base, burning can often only occur when the wind blows to the south (toward the Gulf of Mexico) because of coastal housing developments to the base's east and west. However, rural communities in the South have grown accustomed to some chronic exposure to smoke, particularly at certain times of the year. In the Red Hills area of Georgia and Florida, the end of quail season (the beginning of March) is followed by 6 weeks of smoke. Everyone in the area knows it is a part of the season. However, the Southeast does not commonly get dense, thick plumes that settle in for days or weeks. Hiers thought communities likely prefer 6 weeks of light smoke to such intense plumes. Some recent large wildfires in the Okefenokee Swamp, particularly the fires of 2007, gave Southeast residents a western-type experience with fire, which is something the region would like to avoid repeating in the future.

Allen followed up on Hiers' answer, asking if the type of fuels burned in the Southeast contributes to the acceptance of smoke in that region. Paveglio replied that some recent work has been done on that question by Troy Hall at Oregon State University and colleagues, including the development of a photographic guide to assist smoke management (Hyde et al., 2016). Social science needs these types of tools and heuristics, which exist for biophysical science. Just as Stephens had a number of pictures in his presentation of fuel types that can be quickly recognized, Paveglio wondered if tools and heuristics could be developed so that social conditions or the types of prescriptions for the smoke that people are willing to accept could be quickly recognized. In essence, the same kind of systematic data collection for social science is needed to turn it into usable science.

Champ added that some of her research has looked at the economic cost of wildfire smoke exposure. She has found that the social cost of a large fire can swamp suppression cost, yet much more intellectual energy is devoted to talking about suppression cost. The toolkit available in economics to measure the social costs of smoke is inadequate because the costs that people incur to avoid being exposed to smoke are not considered. Only one economics study in the United States has been done on the cost of averting behavior for wildfire smoke (Richardson et al., 2013). The issue has not received the attention it deserves from researchers. The U.S. Environmental Protection Agency is starting to explore these economic and behavioral costs and is developing an app to help the agency get a better understanding of the choices people make to avoid or not avoid smoke. That kind of information will help researchers, managers, and policymakers better understand the risk–risk tradeoffs of prescribed fire smoke, which include: when people know smoke is coming, will they leave the area, stay indoors, or choose to be exposed to the smoke?

Paveglio added that the way social impacts of fire are understood is not well developed. In general, the metrics are quantitative, such as the number of structures burned and the cost of suppression. In a 2015 paper (Paveglio et al., 2015), he and his colleagues compiled a list of all the different potential social impacts that could occur; the list was extensive and could be broken down into several categories. More thought needs to be directed at assessing the social impacts of fire on different communities, which includes smoke and health risks. A more comprehensive understanding is needed of what the benefits and the detractions are from fire events.

CONCLUDING REMARKS FROM MORNING SESSION

Dar Roberts, University of California, Santa Barbara

As the chair of the planning committee, Dar Roberts offered some summary thoughts about the morning's presentations and discussions. Clearly, a great deal has been learned about fire over the last century. However, there is a still a need to improve fire management. As Chief Tidwell noted, that includes working to get more fire back on the landscape, learning to live with more smoke, and improving fire safety. The workshop also featured a great deal of information about the anthropogenic link to today's fire problem. Humans start most fires. The consequences of fire are not always negative; the challenge is to get the right fires burning in the right places so they can be used to improve ecosystem management. This balance will be increasingly important as climate change puts pressure on ecosystem resilience.

Living with smoke will continue to be a major issue. Even when fire is managed well and prescribed burning is used successfully, mitigating the smoke or getting the public to accept a certain amount of smoke is a challenge connected to fire.

With regard to Chief Tidwell's call to identify the missing science, Roberts said that one area highlighted in the presentations and discussions was the lack of knowledge about how fires spread. The largely empirical model developed by Rothermel is still the core of almost all work involving fire spread, but there are many metrics that probably could be incorporated into fire spread models. That was just one example of many areas of research identified.

6

Breakout Sessions

About 50 participants in the morning discussion partook in breakout sessions in the afternoon. The sessions were designed to tackle the following issues:

- What are the key research efforts by region for the next 5–10 years?
- What are the technologies (for example, data and models) that can be used for fire management and what are the barriers to adoption?
- Integrating science into management and policy
- Stakeholder engagement

The participants were divided into four groups. Each group discussed three of the four session topics. At the conclusion of the rotations, participants reconvened to discuss the outcomes of the afternoon's conversations.

KEY RESEARCH EFFORTS

While discussing key research efforts, participants were asked to keep in mind the following questions:

- How can fire management practices be improved through learning from regional differences in fire ecology?
- How might research priorities change by region in response to climate change?
- How might climate change affect management by region?

The objective was to generate 10 pressing questions for fire science to pursue in the next 10 years. To provide clarity to the parameters of the discussion, regions were defined broadly based on eco-climatological principles, such as Southwest, Northwest, Boreal, Southeast, Midwest, Mountain West, and Northeast.

Dar Roberts moderated this breakout topic. He provided a synthesis of the 10 questions that emerged from the conversations of the three groups that rotated through that session.

1. How best can the impacts and efficacy of steps taken to mitigate the risk of fire and to make the public aware of fire risk be assessed?
2. How can large-scale bark beetle mortality be managed and how might that management affect fire?
3. How can remote measurements be used to understand the behavior and effects of large, active fires?
4. How can incident teams obtain good intelligence on fire location and movement?
5. Given that succession and adaptation in wildland occur over a long period of time, how can the temporal scale of these processes be captured when funding cycles are only a few years in length and the careers of scientists are short in comparison to the ecosystem changes they study?
6. Is there an opportunity for a long-term ecological research network related to fire?
7. How can fire–vegetation–fuels–climate feedbacks be understood from model to empirical scales and in top-down and bottom-up control approaches?
8. How can science and research be leveraged to address changes in where fire is happening and where it has been perceived as not happening (for example, in the Southeast)?
9. How can risks and opportunities be bounded when planning for future changes in fire regimes and their consequences?
10. How can research assist managers to use wildfire and prescribed burns to achieve desirable outcomes?

In addition to managing fire better and helping communities live with fire, many participants thought that finding answers to these questions would help address issues related to wildland fire and climate change, such as determining when to manage burned areas for restoration versus letting the habitat change to a new ecosystem, providing adequate habitat for endangered plant and animal species, and anticipating and planning for changes to hydrology in burned landscapes.

The participants of this breakout session highlighted areas of research deserving attention:

- At the wildland–urban interface (WUI), research on structural fuel management and on improving design or retrofits for structures to make them more resistant to embers.
- Improved tools for predicting smoke dispersal and understanding the physical and mental health effects of smoke on people.
- Better climate models that can project conditions 30–50 years in the future as well as models that can scale down to the level of national and regional climates, even down to the level of fire regimes. Such tools would help forecast climate variability, improve predictions of how ecosystems respond to climate change, and help researchers to understand what fire regimes may work in different areas under future climate conditions.
- More research focused on the human dimensions of fire, including smoke, fuels treatment, and stakeholder engagement.
- Research to better understand and to be able to compare outcomes from different fire management approaches, such as box and burn and fuel breaks. Such research would not only provide information about the cost effectiveness of fire management approaches but would also provide a better understanding of the effects of management practices post-fire on ecosystems and endangered species.

Participants also mentioned that more data need to be collected on drought metrics (for example, snowpack and precipitation), global circulation metrics, large fires, and fuels to create data sets that can be used for long-term (30–50 years) predictions. Making such data widely available to researchers would help advance knowledge about fire quicker. Many participants also thought that knowledge would advance faster if there were more interactions among different disciplines involved with fire (for example, modeling, remote sensing, ecology, and management).

THE ROLE OF TECHNOLOGY: WHAT ARE THE TECHNOLOGIES AND WHAT ARE THE BARRIERS TO ADOPTION?

Participants who rotated through the technology session were asked to answer these questions:

- What are the technologies available for assessing fire risk and fire danger/hazard?
- What are the technologies available for near real-time fire detection, fire monitoring, and short-term fire spread prediction?
- What are the technologies available for mapping and managing post-fire conditions?
- Where are the gaps and barriers in adopting these technologies for operational use?

The goal of their conversations was to pinpoint the top five technologies that could be promoted for use in operational fire and resource management.

Planning committee member Anupma Prakash served as the moderator for the session focused on technology. She presented to the afternoon participants the five top technologies to be promoted for use in operational fire and resource management that surfaced from the afternoon's discussions.

1. Unmanned aerial systems ("drones"). Drones can be put to use for different purposes during fire emergencies, including data collection, communication, and firefighting. Drones can collect data on fire conditions and can use infrared sensors when smoke obscures optical instruments. They can monitor conditions for firefighter safety and monitor landscapes after fire has occurred. Unlike planes, drones can be flown at night, which would increase the amount of data gathered on a given fire. Drones could also be used to deliver fire retardant, perhaps even at night when wind speeds are often lower. Real-time information is critical to fighting fire, but cell phones often do not work in remote wildland fire locations. Drones could help close this communication gap.
2. Imaging at different spectral scales. Different technologies capture images of the land in varying levels of detail. Their effectiveness depends on the landscape; some are more useful in forested areas while others are better at piercing through cloud cover. Multiple technologies—such as multispectral and hyperspectral imaging, synthetic aperture radar, and LIDAR—could be used together to capture different spatial and temporal scales in order to characterize the landscape pre-fire and post-fire. In particular, technologies using different spectral scales would help address the challenge of assessing the subsurface effects of fire.
3. Long-term, field-based calibration and validation of data for quality assessment. These would reduce uncertainty in the data used by managers to make decisions and provide better data to feedback into models.

4. Common terminology and data-capture techniques. The development of common terms would improve the usability of data sets. Investment in low-cost data collection and analysis tools for field settings would increase the data available to fire operations. Better organized data sets would help avert the problem of too much information that sometimes confronts fire operations.
5. Social media and big data. Mining such data sources, including apps that allow people to identify a fire's location, could help improve early fire detection, increase fire monitoring, and improve understanding of stakeholder needs (for communities as well as fire managers). Monitoring hashtags, for example, would convert community members into additional observers.

Other areas where participants thought better technology could help were fuel characterization (in particular, fuel moisture), mapping model predictions of lightning to areas with high fuel loads, and using smoke chemistry and spread to better understand fire behavior and the fuels related to the observed behavior. The importance of mapping unburned areas following a fire to understand the habitat and vegetation differences between burned and unburned land and investigating post-fire effects to understand future fire risks also emerged from these discussions. Some participants said this mapping should be done quickly and often after fires so that post-fire changes—such as flooding, landslides, and sediment runoff—can be fed back into models to help predict conditions that may be expected in a future fire.

Several participants mentioned that 3-dimensional mapping of vegetation would be particularly helpful for assessing fuel conditions on the landscape; at the present time, producing such maps is cost prohibitive. However, if those maps were available, they would only be useful if a companion tool were developed for their use in fire management decisions. To develop such a tool, how fire spreads first needs to be better understood, one participant said; gaining a better understanding of fire spread will require more experimentation with fires fed by different types of fuel.

INTEGRATING SCIENCE INTO MANAGEMENT AND POLICY

In the session about integrating science into management and policy, planning committee member Rod Linn asked participants to consider the following questions:

- What is known in terms of fire science and fire and fuels management that should be used and what are the barriers to that use?
- What does the fire and fuels management and policy community need from the fire science community? What does the former think the latter should be focusing on? What are the challenges for managers/operators in using/applying the fire science available? How can the science best be made available to the end users?
- What are the differences in the science needs for prescribed fire usage versus wildfire management?
- What are good examples of proactive management approaches?

From the discussion generated by these questions, the participants were to highlight three best practices for integrating science with policy and three additional best practices that would be desirable.

Linn summarized the points made in the afternoon when the participants reconvened from the breakout sessions. In terms of the three best management practices for integrating science into policy, the participants suggested (1) the existing Fire Science Exchange Networks (previously Fire Science Consortia), (2) integration of scientists on the fire line, which would give them credibility with fire managers, and (3) finding those fire managers who are receptive to science. The reach of the Fire Science Exchange Networks needs to expand, many participants thought, because at present they do not come into contact with enough fire managers. Another advantage of the exchange networks is that they are regionally based (15 across the United States, including Alaska and Hawaii), so they are attuned to the fire history and regime in a particular area. More engagement between the exchange networks and state-level officials and private landowners would also be useful, a participant observed. Including scientists on the fire line would provide fire managers with a resource to help them determine which ones of the many scientific and fire management tools available have the most utility in a given fire situation.

Additional best practices that participants thought desirable were (1) more opportunities for in-person relationships to be built and maintained between fire scientists and fire managers, (2) better integration of managers at the start of research projects because this would improve the project design and increase the likelihood that the research results will be applied, (3) more research exploring social and institutional science to overcome the cultural barriers that prevent the translation of science into management practices, and (4) continuing education to keep fire managers receptive to science and to help different generations of fire managers maintain a common understanding of the state of the science. Many participants acknowledged that building relationships between scientists and managers and integrating managers into project design takes time and energy, but they thought such steps would have tremendous payoff in terms of developing outputs from scientific research that would be useful to fire managers at a local level. With regard to translating science into practice, multiple forms of communication (e.g., webinars, text messages, and social media) may be needed to engage managers of different ages.

The suggestion for continuing education generated some discussion among the participants. One participant noted that continuing education should be a priority for all resource managers, not just fire managers. It was also suggested that there should be credits or incentives for researchers to work with managers. Someone responded that this type of interaction is increasingly being required of researchers by grant managers; however, the amount of emphasis on that interaction may vary by agency. A Forest Service employee shared that the Forest Service gives equal weight in terms of career accomplishments to technology transferred from laboratory to field application and a peer-reviewed published paper. Steelman noted that co-production of knowledge between researchers and managers is critical for the credibility, legitimacy, and saliency of said knowledge. She added that scientists want their work to be credible, local managers want legitimacy of the work to understand why they should use the science, and information needs to be salient for decision makers to help them take action. Unfortunately, many of the institutions and incentives that govern these three actors are poorly constructed to accomplish these objectives, Steelman concluded.

Linn also reported from the breakout discussions that a number of participants noted that it is important for the fidelity of the science of prescribed fires to be high because there is more scrutiny and responsibility for prescribed fires than for wildfires. He thought that more scientific research needs to be conducted on prescribed fires because they can be most easily manipulated by researchers and managers.

STAKEHOLDER ENGAGEMENT

In their discussions about engaging with stakeholders, participants particularly focused on the following questions:

- What is the role of co-management in differentiating and addressing "good fires" versus "bad fires"?
- What are the critical social, political, and economic challenges associated with differentiating, labeling, and responding to "good fires" versus "bad fires" in the WUI?
- What are best practices in stakeholder engagement that can facilitate more flexible fire management of "good fires"? How can the public and policymakers be brought into this conversation?

Participants sought to pinpoint 3–5 key challenges to differentiating and labeling good fires versus bad fires and to suggest 3–5 best practices or strategies for working among diverse stakeholders to create conditions that allow for more flexible fire management when appropriate.

Workshop presenter Toddi Steelman moderated this discussion and presented the summary findings to all the participants. She noted that breakout participants did not like the polarization of fire into the categories of *good* and *bad*. A fire that could be bad in the short term may be good in the long term. Good is often equated with favorable political outcomes or connected to ecological conditions, whereas bad is associated with the loss of businesses or structures and with loss of life. Rather than good and bad, fires need to be thought of more in terms of risk management and the tradeoffs associated with different management decisions. Those decisions need to incorporate a temporal component, considering short-term and long-term implications of management actions.

Most participants agreed that communication is a key challenge; communicating the varying benefits, objectives, and tradeoffs related to fire is complex. This complexity is evident in the inability to categorize fires simply as good or bad.

Other challenges to fire management mentioned by some participants include:

- An insufficient understanding of the health effects of smoke.
- The Endangered Species Act, the Clean Air Act, and the Healthy Forests Restoration Act have competing and unharmonized objectives.
- Legal challenges to prescribed fire, which can prevent its use and leave land management agencies or actors open to liability and gross negligence when fire is used or when it is not and untreated fuels goes on to cause large fires.

According to some participants, co-management could be a suitable practice for working with diverse stakeholders to create conditions that allow for more flexible fire management. Co-management is a process that can create opportunities to share ideas, deliberate tradeoffs, and find common ground that is appropriate for the context and the place under discussion. Some participants noted that field trips could help with reaching agreement in communities to help diverse stakeholders better understand the risks and tradeoffs. Others said federal, state, local, and private land managers need to come together long before a fire occurs to be in a position to readily implement land and fire management plans when needed.

Another practice mentioned by some participants is the creation of opportunities for sustained community engagement, which would facilitate more flexible fire management. Messages that are correctly tailored to the context and delivered by people trusted in the community, for example, prescribed fire councils or fire chiefs, would help this engagement. Prescribed fire councils could also be a conduit for air quality conversations, a few participants added. It is important that the communication strategy emphasizes hope, not fear. Several participants noted state foresters also need to be involved because they are typically in place over a long period of time. A few participants mentioned media and zoning commissions are other players who should be involved.

Just as engagement with communities is desirable, many participants thought that similar efforts with policymakers and politicians would also be worthwhile. Opportunities on this front include:

- Resurrecting the Joint Fire Science Policy Consortium in Washington, DC, and empowering it to interact with members of Congress.
- Encouraging more interactions of researchers and managers with congressional members of the Hazard Caucus Alliance.
- Reviving the Wildland Fire Leadership Council, an intergovernmental committee that supports implementation and coordination of federal fire management policy. At the time of the workshop, the council was inactive because of the change in presidential administrations.
- Establishing a Federal Fire Science Coordinating Council, recommended in a 2015 report on wildland fire science and technology by the National Science and Technology Council in the Executive Office of the President (NSTC, 2015).

Some participants noted that engaging policymakers and politicians, particularly Congress, through these means would help to communicate the message that the costs associated with fire extend far beyond the amount spent on fire suppression.

Finally, Steelman said that there needs to be more focus on using fire events as opportunities to educate stakeholders, which could help develop a common understanding of the risks and tradeoffs involved with fire. More work lies ahead on messaging after a fire.

SUMMARY OF BREAKOUT SESSIONS

The breakout sessions were structured to respond to wildland fire research status, needs, and challenges outlined in the statement of task, specifically:

- Helping wildland fire managers and responders discriminate between “good” and “bad” fires;
- Adaptive fire and forest management;
- Proactive approaches to landscape level fuel management; and
- Societal needs and considerations to support and implement long-term wildland fire management strategies.

With regard to the first item, it was clear that many participants, particularly those who participated in the stakeholder engagement breakout session, thought that the dichotomy of “good” and “bad” fire was too strong. Instead, whether a fire is “good” or “bad” can depend on the point of view of the stakeholder and the point in time from which the aftermath of a fire is considered. Fires that cause destruction to human developments may later prove to have favorable effects on ecosystem health. Therefore, many participants emphasized the importance of taking the context of fire into consideration, including who may be affected by the fire, what kind of ecosystem a fire may burn, and what the management objectives of a fire-prone community may be. Most participants thought that managing fires with community input will help fire scientists, fire managers, and community members better understand the risks and tradeoffs involved in living with prescribed fire and wildfire and may increase all parties' ability to understand the nuance associated with fire's risks and benefits, which change over time.

Many workshop participants said that reaching common ground through co-management of fire with communities will likely help with the three other items outlined in the statement of task. Such local engagement will be important because of the variety of fire regimes throughout the United States and the increasing number and changing demographics of people living in the WUI.

With regard to the data needs that will help adaptive management of fire, forests, and fuels, it emerged in more than one breakout session that data need to be more streamlined. Data that are more uniform can be shared more easily among fire scientists, and the knowledge generated from that data can be passed on to fire managers faster if it is harmonized. Data on more metrics, such as drought and wind, would be helpful for making long-term (30–50 years) predictions. The need for improved climate and meteorological modeling tools was also voiced by several participants. Some participants advocated for more experimentation with fire, rather than just through modeling, to better understand the effects of different fuels and fuel structures on fire spread. More studies of post-fire habitats, particularly comparisons between burned and unburned land following a fire, would provide information about future fire risks; some participants thought that such research in different fire regimes would be beneficial because a better understanding of post-fire effects would help fire scientists and fire managers communicate with communities about the fire risks and tradeoffs specific to their area. Technologies such as drones and imaging tools at multiple spectral scales could help collect much of the data that would inform better adaptive management approaches for fire, forests, and fuels.

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Glossary

Crown fire — A forest fire that has ascended from the ground into the forest canopy and spreads from treetop to treetop, often with great speed.

Ecoregion — An ecological and geographically defined area with geographically distinct assemblages of natural communities and species.

Fire regime — The range of variability in fire characteristics in a given area over a set period of time. It includes fire frequency, predictability, intensity, seasonality, and size.

Fuels treatment — Any measurable procedure taken to lower the risk of wildfires by managing vegetation to reduce hazardous fuels. Example actions include prescribed burning and mechanical thinning of forests.

Light burning — The use of fire at regular intervals as a management tool for ecosystem or livelihood objectives.

Line officer — The official responsible for administering policy on an area of public land. The official has full authority for making decisions about and providing direction to the firefighting effort.

Managed wildfire — Any unplanned wildfire used to meet specific objectives.

Mosaic — Burned habitat patches of different sizes and degrees of severity in proximity to one another as a result of a wildland fire or a history of wildland fires.

Prescribed fire	Any planned fire ignited by management actions to meet specific objectives.
Wildfire	Unplanned fire in wildland, regardless of ignition source.
Wildland fire	A general term describing any nonstructure fire that occurs in wildland areas and burns natural fuels, such as trees and grass.
Wildland–urban interface	A zone where structures and other human developments meet and intermingle with undeveloped wildland.
Woodsburning	The regular burning of forested areas, a practice common in the southeastern United States.

Appendix A

Workshop Agenda

National Academy of Sciences Building
2101 Constitution Avenue, NW
Washington, DC

Monday, March 27, 2017

PLENARY SESSION

7:45 REGISTRATION

8:30 WELCOME AND INTRODUCTORY REMARKS
Gregory Symmes, Executive Director, Division on Earth and Life Studies, National Academies of Sciences, Engineering, and Medicine
Dar Roberts, Chair, Workshop Planning Committee Chair, University of California, Santa Barbara

8:35 REMARKS FROM THE U.S. FOREST SERVICE
Deputy Chief Carlos Rodriguez-Franco
Chief Thomas Tidwell
Diane Smith, Research Historian

9:05 INTRODUCTION OF KEYNOTE SPEAKERS

9:10 KEYNOTE: FIRE SCIENCE'S AMERICAN CENTURY
Stephen J. Pyne, Arizona State University

9:55 KEYNOTE: FUTURE OF FIRE IN THE UNITED STATES
Jennifer K. Balch, University of Colorado, Boulder

10:30 BREAK

PANEL DISCUSSIONS

10:45 UNDERSTANDING FIRE: STATE OF THE SCIENCE AND RESEARCH PRIORITIES

Moderator: Monica G. Turner (NAS), Workshop Planning Committee Member, University of Wisconsin–Madison

Fire regimes and the ecological role of fire in U.S. landscapes
Meg Krawchuk, Oregon State University

Predicting and mapping fire and fire effects
Mark Finney, U.S. Forest Service

Changing environmental drivers, tipping points, and resilience in fire-prone systems
Craig D. Allen, U.S. Geological Survey

Fire and fuels management: What works where?
Scott Stephens, University of California, Berkeley

11:45 LIVING WITH FIRE: STATE OF THE SCIENCE AROUND FIRE-ADAPTED COMMUNITIES

Moderator: Jeffrey Rubin, Workshop Planning Committee Member, Tualatin Valley Fire and Rescue

Understanding the wildfire policy context: Where are we now?
Toddi Steelman, University of Saskatchewan

Community variation in relationships and response to wildland fire
Travis Paveglio, University of Idaho

Translating fire science into fire management: State of the field, challenges, and opportunities
J. Kevin Hiers, Tall Timbers Research Station & Land Conservancy

Wildland fire risk perceptions and mitigation behavior
Patty Champ, U.S. Forest Service

12:45 SYNTHESIS OF KEY THEMES AND CLOSING REMARKS
Dar Roberts, Chair, Workshop Planning Committee

1:00 ADJOURN PLENARY SESSION

1:30 AFTERNOON BREAKOUT SESSIONS

4:00 REPORTS FROM BREAKOUT SESSIONS

5:00 FUTURE STEPS AND CLOSING REMARKS

5:15 ADJOURN WORKSHOP

Appendix B

Biographies of Workshop Planning Committee

Dar Roberts is a professor in the Department of Geography at the University of California, Santa Barbara (UCSB), where he started in January 1994. He is the UCSB Principal Investigator of the Southern California Wildfire Hazard Center and leads the group in developing wildfire fuels maps and mapping fuel moisture using remote sensing. Dr. Roberts has authored 169 refereed publications, more than 21 books/book chapters, and over 100 abstracts and nonrefereed articles. His research interests include imaging spectrometry, remote sensing of vegetation, spectroscopy (urban and natural cover), land-use/land-cover change mapping with satellite time series, height mapping with LIDAR, fire danger assessment, and, recently, remote sensing of methane. He has worked with hyperspectral data since 1984 and broadband sensors over the same period, as well as Synthetic Aperture Radar. Dr. Roberts also holds an M.A. in applied earth sciences from Stanford University and B.A. degrees in geology and biology from the University of California, Santa Barbara. He received his Ph.D. in geological sciences from the University of Washington in 1991.

Rodman R. Linn is a senior scientist at Los Alamos National Laboratory (LANL). He also serves as subject matter expert for a variety of LANL, U.S. Department of Energy, and Defense Threat Reduction Agency programs concerning wildfire science and connections between wildfire and national security, including those associated with evolving climate conditions. Additionally, he leads research areas of urban fires, wind energy, dispersion, and canopy/atmosphere interaction. Dr. Linn was an associate editor for the *International Journal of Wildland Fire* from 2005 until 2016 and was an associate director for the California Institute of Hazards Research from 2007 to 2011. Early in his career, he developed a new type of physics-based coupled fire/atmosphere wildfire model utilizing computational fluid dynamics techniques, FIRETEC, which became the first three-dimensional physics-based coupled fire/atmosphere computer model designed to work on landscape-scale fires. Dr. Linn continues to push the forefront of physics-based models for the study of fundamental wildfire behavior, evaluation of prescribed fire tactics, and understanding of complex environmental conditions on fire behavior, risk assessment, and wildfire's interaction with other landscape disturbances. He holds M.S. and B.S. degrees in mechanical engineering from the University of Illinois, Urbana-Champaign, and New Mexico State University, respectively. He received his Ph.D. in mechanical engineering from New Mexico State University in 1997.

Branda L. Nowell is a professor in the School of Public and International Affairs at North Carolina State University and is currently serving as the director of the Doctoral Program in Public Administration. Dr. Nowell's research focuses on multiorganizational system design and governance, interorganizational relationships, social networks, and community capacity for multiagent collaboration and coordination within complex problem domains. She is the co-founder and director of the Firechasers Research Program which studies the interaction of local, state, and federal systems before and during complex wildfire events with the goal of advancing the science of adaptive capacity toward more disaster resilient communities. Since 2008, this team has worked in collaboration with the U.S. Forest Service and other land agency partners on research aimed to improve interagency coordination and communication during large-scale wildfire events. Dr. Nowell's research has received awards from the Society for Community Research and Action and the Academy of Management, Public and Nonprofit Division. Her published work appears in a multidisciplinary array of journals. Dr. Nowell holds an M.S. in conflict resolution from Wayne State University and a B.S. in psychology from Boise State University. She received her Ph.D. in organizational/community psychology from Michigan State University in 2006.

Anupma Prakash is a professor of geophysics at the University of Alaska, Fairbanks (UAF). She is the associate dean for UAF's College of Natural Science and Mathematics (CNSM) and the director for CNSM Division of Research. Her research involves using field methods, remote sensing, and modeling for mapping Earth surface composition and change. Dr. Prakash is the principal investigator of the National Science Foundation–funded Alaska Experimental Program to Stimulate Competitive Research (Alaska EPSCoR) Program. She researches changing wildfire regimes in high latitudes by using advanced remote sensing and modeling techniques to characterize and monitor them. Additionally, this research spans to adaptive management practices to mitigate the causes and effects of wildfires at local and regional scales. Dr. Prakash is internationally recognized for her research investigating surface and underground coal mine fires. She holds an M.S. in geology and B.S. degrees in geology, botany, and zoology, all from Lucknow University in India. Dr. Prakash received her Ph.D. in earth sciences from the Indian Institute of Technology at Roorkee in 1996.

Jeffrey N. Rubin is the emergency manager for Tualatin Valley Fire and Rescue, Oregon's largest fire district. His work focuses on hazard and threat analysis, planning, and risk perception and communication. Dr. Rubin serves on the U.S. Department of Homeland Security First Responder Resource Group and the National Institute of Standards and Technology Community Resilience Panel. He was the vice chair of the Governor's Task Force on Resilience Plan Implementation in Oregon. He is a Fellow of the Geological Society of America, a Certified Emergency Manager, and a Nationally Registered Emergency Medical Technician. He holds an M.A. in geological sciences from the University of Texas at Austin and a B.S. in geology and geophysics from Yale University. He received his Ph.D. in geological sciences from the University of Texas at Austin in 1996.

Monica G. Turner (NAS) is the Eugene P. Odum Professor of Ecology and a Vilas Research Professor in the Department of Zoology at the University of Wisconsin–Madison. Her research emphasizes causes and consequences of spatial heterogeneity in ecological systems, focusing primarily on ecosystem and landscape ecology. She has studied fire, vegetation dynamics, nutrient cycling, bark beetle outbreaks, and climate change in Greater Yellowstone for over 25 years, including long-term research on the 1988 Yellowstone fires. She also studies abrupt change in ecological systems, land-water interactions in Wisconsin landscapes, effects of current and past land use in Southern Appalachian forests, and spatial patterns of ecosystem services. She has published nearly 250 scientific papers, authored or edited six books, including *Landscape Ecology in Theory and Practice*; and is co-editor in chief of *Ecosystems*. Turner is past-president of the Ecological Society of America (ESA), a recipient of ESA's Robert H. MacArthur Award, and a member of the National Academy of Sciences. She earned her B.S. in biology from Fordham University in 1980 and her Ph.D. in ecology from the University of Georgia in 1985.

Appendix C

Biographies of Workshop Presenters

Craig D. Allen is a research ecologist and station leader for the U.S. Geological Survey at the New Mexico Field Station. He has worked as a place-based field ecologist for the U.S. Department of the Interior since 1986, co-located with land managers at Bandelier National Monument in the Jemez Mountains of northern New Mexico—a landscape that has been subject to multiple significant wildfires since 1996. Dr. Allen conducts research on the ecology and environmental history of southwestern U.S. landscapes and the responses of western mountain ecosystems and forests globally to climate. He also provides technical support in the areas of ecosystem management and restoration to diverse land management agencies in the region. Recent and ongoing research activities, involving diverse collaborations, include: determination of global patterns, trends, and drivers of climate-induced tree mortality and forest die-off; ecological restoration of southwestern forests and woodlands; and developing long-term ecological monitoring networks in New Mexico.

Jennifer K. Balch is Director of Earth Lab and an assistant professor in the Department of Geography at the University of Colorado, Boulder. Dr. Balch's research aims to understand the patterns and processes that underlie disturbance and ecosystem recovery, particularly how people are shifting fire regimes and the consequences. Her work spans from temperate regions to the tropics exploring how fire alters rainforests, encourages nonnative grass invasion, and affects the global climate. Prior to coming to the University of Colorado, she was on the faculty at the Pennsylvania State University. She was a postdoctoral associate at the U.S.-based National Center for Ecological Analysis and Synthesis and received her Ph.D. from Yale University's School of Forestry and Environmental Studies. She has conducted research in the field of fire ecology for over a decade and has lit a few experimental burns to understand the consequences of altered fire regimes.

Patricia Champ is a research economist with the U.S. Forest Service, Rocky Mountain Research Station in Fort Collins, Colorado. She has been with the research station since she completed graduate school 23 years ago. Dr. Champ has developed a research program that focuses on three aspects of wildfire: the economic costs of exposure to wildfire smoke, the effects of wildfire risk on home sales prices, and wildland–urban interface homeowners' perceptions of risk and risk-mitigating behaviors. Her most recent work examines how behavioral economic techniques can be used to encourage homeowners to mitigate wildfire risk.

Mark A. Finney is a research forester with the U.S. Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory. His research has addressed landscape fuel management and fire behavior, fire growth modeling, wildfire risk analysis, and ignition by firearms and explosives. He and his team are now discovering physical explanations for wildland fire behavior using laboratory and field-scale experiments. In 1991 he was awarded his Ph.D. in wildland fire science from the University of California, Berkeley. He also holds an M.S. in fire ecology from the University of Washington and a B.S. in forestry from Colorado State University.

J. Kevin Hiers is a wildland fire scientist at Tall Timbers Research Station in Tallahassee, Florida. Hiers has a 20-year background in wildland fire management with particular expertise in prescribed fire. In his current role he is responsible for creating a research program that focuses on management application of prescribed fire science. Prior to joining Tall Timbers, Hiers worked as director of environmental stewardship at the University of the South in Sewanee, Tennessee, as acting chief of the Air Force Wildland Fire Center, and as Eglin Air Force Base fire program manager.

Meg A. Krawchuk is an assistant professor in the Department of Forest Ecosystems and Society in the College of Forestry at Oregon State University. Dr. Krawchuk leads the Landscape Fire and Conservation Science Research Group, with research and teaching focused on landscape and fire ecology, pyrogeography, and conservation science. Recent investigations include: predictability, form, and function of fire refugia within burn mosaics of the western North American forest ecosystem; ecological implications of overlapping short-interval disturbances such as insect outbreaks, forest harvest, and wildfire; spatially varying constraints over modern patterns of burning at regional and global scales; and theory and tools necessary for science-based conservation planning in boreal forest ecosystems of Canada and the United States. Dr. Krawchuk was awarded her Ph.D. from the University of Alberta, Canada, completed postdoctoral work at the University of California, Berkeley, and was a faculty member at Simon Fraser University, Canada, prior to joining the faculty at Oregon State University.

Travis Paveglio is an assistant professor of natural resource sociology in the Department of Natural Resources and Society at the University of Idaho. His research focuses on the human and policy dimensions of wildfire management (e.g., evacuation policies, fuel reduction planning, homeowner mitigation actions, suppression actions, identification of values-at-risk, and recovery aid), with an overarching emphasis on the ways that diverse populations adapt to changing wildfire risk and develop relationships with the landscape. Dr. Paveglio has spent more than a decade conducting qualitative and quantitative case studies of collaborative wildfire risk management, response, and recovery in dozens of communities across the western United States. He received training in natural resource sociology, communication, and ecology.

Stephen J. Pyne is a professor in the School of Life Sciences, Arizona State University. In his youth he spent 15 seasons with the North Rim Longshots at Grand Canyon National

Park and three seasons writing fire plans for Rocky Mountain and Yellowstone National Parks. His books on the American fire scene include *Fire in America: A Cultural History of Wildland and Rural Fire* (1982), *Year of the Fires* (2001), and most recently *Between Two Fires: A Fire History of Contemporary America* (2015) and *To the Last Smoke*, a suite of regional fire surveys. Other fire books include histories for Australia, Canada, Europe (including Russia), and the Earth, along with a popular survey, *Fire: Nature and Culture* (2012), and a textbook, *Introduction to Wildland Fire* (1984, 1996). Among his other works are *Grove Karl Gilbert* (1980); *How the Canyon Became Grand* (1998); *The Ice: A Journey to Antarctica* (1986); *Voyager: Exploration, Space, and the Third Great Age of Discovery* (2010); *The Last Lost World* (co-written with Lydia V. Pyne, 2012); and *Voice and Vision: A Guide to Writing History and Other Serious Nonfiction* (2009). He teaches courses on fire, the history of exploration, environmental history, and nonfiction writing.

Carlos Rodriguez-Franco is Deputy Chief of the U.S. Forest Service. He is responsible for providing national leadership to comprehensive scientific programs, many of which have worldwide impact on providing fundamental and applied knowledge to important environmental, conservation, and utilization problems. His specific responsibilities cover an exceptionally broad and complex array of research spanning multidisciplinary components that must be successfully integrated to solve vegetation management and protection knowledge and technology gaps. Before joining the Forest Service, Dr. Rodriguez-Franco worked in the USDA's Agricultural Research Service where he was based in the Office of International Research Programs. Dr. Rodriguez-Franco received his Ph.D. in forestry from Yale University and has more than 30 years' experience in research, academic, and administrative forestry positions.

Diane M. Smith is in her final year as a postdoctoral research historian at the Missoula Fire Sciences Laboratory, part of the U.S. Forest Service's Rocky Mountain Research Station. While at the Fire Lab, Dr. Smith has written about the origins of wildland fire research, the reintroduction of fire into wilderness areas in the early 1970s (the White Cap Wilderness Fire Study), and the 1988 fires in Yellowstone National Park. In addition to her work with the Fire Lab, Dr. Smith has written numerous national reports and four books, including *Sustainability and Wildland Fire* (Forest Service, 2017) on the origins of wildland fire research in the Forest Service and *Yellowstone and the Smithsonian* (Kansas, 2017) about the history of wildlife conservation in Yellowstone National Park and the Smithsonian Institution.

Toddi A. Steelman is Executive Director and Professor, School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Canada. Her broad research agenda focuses on improving the governance of environmental and natural resources, with emphasis on the role of the public and community in science, policy, and decision-making interactions. She has a 15-year history working on the human dimensions of wildfire and has conducted research on community aspects of wildfire management in Canada and the United States. Her research agenda has focused on understanding community responses to wildfire and how communities and agencies interact for more effective wildfire management. Dr. Steelman is also co-director, with Dr. Branda Nowell, of the Firechasers Research Program at North Carolina State University (www.firechasers.ncsu.edu), which focuses on advancing the science of adaptive capacity toward more disaster resilient communities.

Scott Stephens is a professor of fire science and chair of the Division of Ecosystem Science at the University of California, Berkeley. He is also the director of the university's Center for

Fire Research and Outreach and co-director of the Center for Forestry. He is the leader of the California Fire Science Consortium, which works to more effectively deliver fire science information to natural resource managers. Dr. Stephens' areas of expertise focus on interactions of wildland fire and ecosystems. This includes how prehistoric fires once interacted with ecosystems, how current wildland fires are affecting ecosystems, and how management and climate change may change this interaction. He is also interested in wildland fire policy and how it can be improved to meet the challenges of the next decades.

Thomas L. Tidwell is Chief of the U.S. Forest Service. He has contributed more than 40 years of public service as a natural resources management professional of the Forest Service. He has served in a variety of positions at all levels of the agency, including district ranger, forest supervisor, and legislative affairs specialist in the Washington Office. As deputy regional forester for the Pacific Southwest Region, Tidwell facilitated collaborative approaches to wildland fire management and myriad forest management issues to maintain support for forests and grasslands across a broad spectrum of citizens. As regional forester for the Northern Region, Tidwell strongly supported community-based collaboration in the region, finding solutions based on mutual goals; thereby reducing the number of appeals and lawsuits, while increasing work on the ground. In 2009, after being named Chief, Tidwell set about implementing a vision that met the goals for the agency's mission. Under his leadership, the Forest Service has accelerated treatments on the landscape to improve the health and resiliency of forests and grasslands so they can sustain all the benefits Americans get from their wildlands. This also includes job production, stability of rural communities, and support for tourism-based economies.