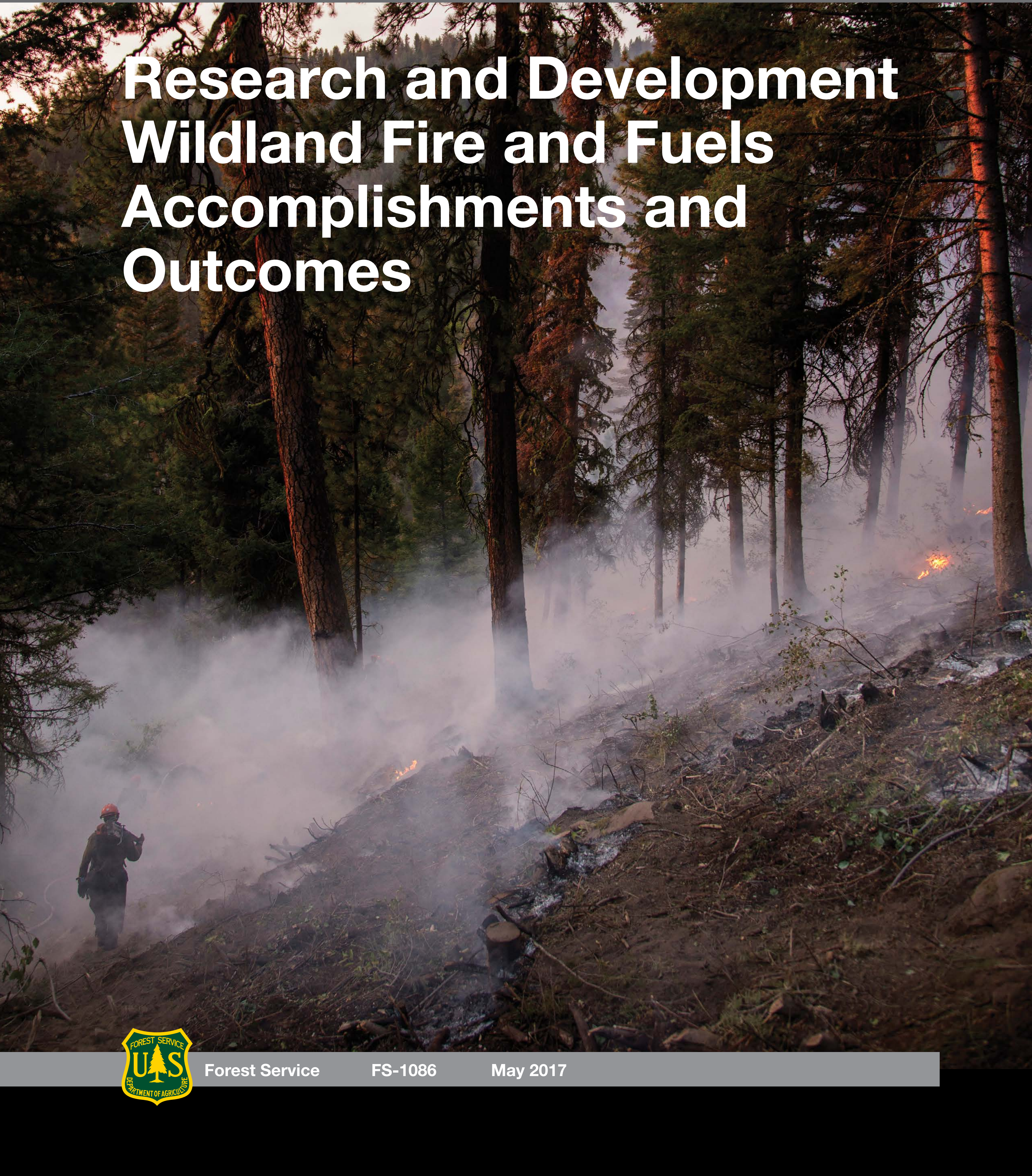
United States Department of Agriculture

# Research and Development Wildland Fire and Fuels Accomplishments and Outcomes



Forest Service FS-1086 May 2017

United States Department of Agriculture

# Research and Development Wildland Fire and Fuels Accomplishments and Outcomes

Matthew Rollins
National Program Leader for Wildland Fire and Fuels
Forest Service, Research and Development
Washington, DC

Carlos Rodriguez-Franco
Deputy Chief
Forest Service, Research and Development
Washington, DC

Tara Haan
Fellow, Oak Ridge Institute for Science and Education
Forest Service, Research and Development
Washington, DC

Susan Conard (Retired)
Forest Service Research and Development
Fairfax, VA

Forest Service FS-1086 May 2017

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720–2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877–8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at http://www.ascr.usda.gov/complaint_filing_cust.html and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632–9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250–9410; (2) fax: (202) 690–7442; or (3) email: program.intake@usda.gov.

USDA is an equal opportunity provider, employer, and lender.

# Contents

# Executive Summary

This report focuses on wildland fire management and response outcomes—in the context of fire and fuels research and development (R&D) at the Forest Service, an agency of the U.S. Department of Agriculture (USDA)—that have transformed the business of wildland fire in the United States. This research has resulted in knowledge, data, and applications that have contributed greatly to the following outcomes.

### **Outcome 1.** Enhanced Physical Fire Science

Wildland fire managers and responders are able to predict the occurrence, extent, and severity of fires with more precision and accuracy resulting in better decisionmaking, resource allocation, and firefighter and public safety. National systems that characterize fire danger and risk are maintained and innovated.

### **Outcome 2.** Better Access to Smoke and Emissions Tools

Practitioners and regulators have access to information and tools for estimating smoke and emissions from wildland fire to support decisions about suppression, managed wildfires, and prescribed fire implementation, primarily to address firefighter and public health and safety.

### **Outcome 3.** Advanced Wildland Fuels Management

Wildland fuels are characterized using consistent and comprehensive science and technology to meet diverse objectives and ensure effective investment strategies to restore resilient landscapes, mitigate wildfire risk, and deliver benefits to the public.

### **Outcome 4.** Improved Social and Economic Context for Wildland Fire Management and Response

The public is aware of the costs and benefits of wildland fire management and response, and socioeconomic research and development are foundations for large landscape collaboration, organizational performance and effectiveness, and firefighter and public safety. Fire management organizations have access to information and tools to improve performance through learning and innovative leadership.

### **Outcome 5.** Strengthened Wildland Fire Ecology Practices Supporting Landscape Restoration

Diverse and comprehensive information and tools that characterize the ecologic costs and benefits of fire are available to support the restoration of resilient landscapes; deliver clean, abundant water; and strengthen communities. Accessible science and technology exist for adaptive and collaborative fire management in the face of changing baseline conditions.

# Introduction

The Research and Development (R&D) Wildland Fire and Fuels program at the Forest Service, an agency of the U.S. Department of Agriculture, continues to be an internationally renowned program for generating critical and essential data, knowledge, and applications for all phases of wildland fire management and response. This report provides a primer on the breadth and depth of Forest Service wildland fire and fuels R&D and synthesizes the robust and diverse body of recent Forest Service fire research in the context of outcomes that have improved the wildland fire management and response in the United States.

## Background

Wildfire management poses unique challenges. Although every year wildfires have significant negative impacts on human communities (e.g., fatalities and injuries, damaged or destroyed homes and infrastructure, poor air quality), in many ecosystems, wildfires are also a critical and beneficial ecological process. Nearly every landscape in the United States has a history of fire, but the patterns of fire frequency, size, and severity have changed over time in response to changes in climate, land use, and exotic invasions (Scott et al. 2014). The cascading effects of more than a century of fire exclusion and fuel buildup, changes in land use, extended drought, warming temperatures, and the spread of invasive species, however, have led to widespread changes in fire regimes across the United States. In many landscapes, wildfire has been excluded by effective suppression, and, as a result, wildland fuels have accumulated and, correspondingly, the size and severity of uncharacteristic fires have increased dramatically. In other landscapes, fire frequency has actually increased because of human-caused ignitions or invasive species and, in other landscapes, such as large wilderness areas, fire regimes remain essentially unchanged.

These changes have added further complexity to an already complex issue. Wildfire risk to highly valued resources, critical infrastructure, and environmental quality generally is expected to continue to escalate as communities continue to expand into the wildlands; changing climate leads to increased temperature and varying precipitation patterns; and the complexity, frequency, size, and severity of wildfires increases (McKenzie et al. 2011). Between 2008 and 2015, an average of 6.3 million acres a year burned in the United States (http://www.nifc.gov), which is about 170 percent of the average annual area burned between 1985 and 2007. Costs to society have also been increasing. Federal agencies now spend an average of more than $1.7 billion per year on fire suppression. Additional millions are spent on wildfire recovery activities by State, tribal, and local governments and by public and private organizations such as utility and insurance companies. Losses from damage to resources and infrastructure and the economic impacts of wildfires can be many times the cost of suppression alone (AFE and TNC 2015). Wildland fire and land managers are thus challenged with balancing the positive effects of fire in many landscapes with the risks posed to communities and ecosystem values from historically uncharacteristic wildfires. This challenge is compounded by the uncertainty surrounding the changing nature of wildfires in the decades to come.

## Wildland Fire Science in the Forest Service

The R&D Wildland Fire and Fuels program has a rich history in the Forest Service, where its most successful periods resulted from partnerships with the fire management community. The mission of the R&D Wildland Fire and Fuels program is to support science and technology needs of Federal, State, tribal, and local governments, and also private land managers, by delivering knowledge that enables the mitigation of wildfire risk and fostering resilient, adaptive ecosystems to mitigate climate change. The Forest Service R&D Deputy Area strives to be recognized as a global leader in delivering innovative knowledge and applications for sustaining global forest resources for future generations. Forest Service R&D provides information and solutions to sustain forests and grasslands and deliver benefits to the public, and it applies this knowledge globally. Working closely with the leaders of wildland fire management organizations, practitioners, incident command teams, and wildfire responders, Forest Service R&D has played a vital role in U.S. wildland fire management and response programs since the early 1900s and continues to develop new knowledge and products that support evolving fire management and response needs in the context of the growing complexity of fires in the United States (USDA Forest Service 2006).

Three influential examples of Forest Service R&D's contributions, developed more than a quarter of a century ago, that have changed the way fire managers in the United States and other countries manage and respond to wildland fires are as follows:

1. **The Incident Command System (ICS)** provides the common management structure that all wildland firefighters and support personnel work under when they come together and respond to an unwanted wildland fire or other incident. The system was developed as part of the Riverside FireScope Research, Development, and Applications (RD&A) program in the 1970s and has been used since its inception in Federal fire response. Over time, the system has been adopted by emergency responders around the world and, in 2001, as a result of the important role it played in the 9/11 response, ICS became the management structure used to manage all natural and human-caused disasters in the United States.
2. **The National Fire Danger Rating System (NFDRS)** is used by wildland fire managers to assess seasonal progression of fire danger, allocate firefighting assets, determine use restrictions, and communicate fire risk with the public.
3. **Fire behavior prediction systems that use the Rothermel (1972) model** are used by Federal agencies and others to predict fire behavior on wildland fires. This model is employed as the core of many fire behavior and decision-support applications that rely on fire spread prediction.

Forest Service R&D management's vision is that new knowledge and applications produced by the Wildland Fire and Fuels program will continue to inform the way that Federal, State, tribal, and local governments and other organizations—

- Establish and maintain resilient landscapes.
- Promote fire-adapted human communities.
- Safely and effectively respond to wildfires.
- Deliver benefits to the public by decreasing the negative effects of wildfires.
- Effectively deliver new knowledge and applications globally.

In this report, we detail the specific Forest Service R&D knowledge and applications developed in recent years and how they have transformed the way that wildland fire leadership and practitioners across the United States manage wildland fire and respond to wildfires and have led to significant positive outcomes in the business of wildland fire and benefits to the public.

## Program Description

Our mission is to support R&D needs of Federal, State, tribal, and local governments and private land managers. Forest Service R&D scientists collaborate with partners in other Federal agencies, industry, nongovernmental organizations, colleges and universities, State forestry organizations, and other governmental agencies. Research benefits the owners and managers of working forests and rangelands and also wildernesses and other protected areas, and it helps restore healthy forests and protect communities. Forest Service R&D has the flexibility to address today's issues effectively and to anticipate tomorrow's needs. Research is conducted at five regional research stations, the International Institute of Tropical Forestry, and the Forest Products

Laboratory (FPL) by 498 scientists, working in 67 locations and covering 45 Research Work Units (RWUs) throughout the United States and in Puerto Rico. The regional areas of coverage of the research stations and the location of the FPL are shown on the map in figure 4 of the Appendix. Each research station is managed by a station director, who has primary responsibility for allocating resources, managing personnel, and structuring and implementing programs within the station. Station directors report directly to the Chief of the Forest Service.

## Forest Service R&D Program Planning and Evaluation

Forest Service R&D has focused on strengthening the conformance of its research program to the President's Management Agenda criteria for Federal research agencies: relevance, quality, and performance.

Although research stations vary somewhat in their structure, each station has a basic working unit that performs research in specific areas. The basic unit in most stations historically has been the RWU—in general, a group of three to eight scientists working on a common set of problems. With increasing need for interdisciplinary research and increasing pressure to decrease the number of scientists carrying out administrative duties, most stations are moving to a structure of larger programs, with flexible teams within them, that can be more responsive to changing priorities and budgets. Individual programs or RWUs in each research station are reviewed periodically for alignment with national and regional priorities. All research groups (programs or RWUs) in the Forest Service are required to operate under formal charters, which are developed based on input from users, internal and external peers, and headquarters staffs. Charters are reviewed and approved both by the station director and by one or more staff directors in the Washington Office. Most programs are chartered for a 5-year period. The chartering process includes reviewing past accomplishments and evaluating capacity and emerging priorities. We expect the results and recommendations of research stations and reviews of national programs to provide significant inputs into this process.

Additional processes are in place for reviewing individual scientists and also research plans and work products. Individual scientists undergo periodic peer review and evaluation of their positions and accomplishments through the Research Panel Process, which is similar to many faculty review processes at universities. Peer review processes are also in place for both study plans and manuscripts intended for publication. Each research station has a quality assurance/quality control (QA/QC) plan that is tied to the national Forest Service R&D QA/QC plan. During 2014, a restructuring of the Forest Service R&D headquarters staff was initiated to improve responsiveness of the R&D Deputy Area to the Investment Criteria. This restructuring has enhanced the agency's ability to document and improve relevance, quality, performance, and efficiency of R&D programs.

## Forest Service R&D Strategic Program Areas

Complementing strategic-level processes is the decision by the Deputy Chief of Forest Service R&D to move toward a research program organization that emphasizes Strategic Program Areas (SPAs). The seven research SPAs are (1) wildland fire and fuels, (2) invasive species, (3) water and air, (4) wildlife and fish, (5) recreation, (6) resource management and use, and (7) inventory and monitoring. National teams have been established in each of these SPAs to provide more coordinated program planning for those issues that transcend the regional boundaries of research stations and to provide better ways of describing the agency's research programs to the Administration, the Congress, and the public. The Wildland Fire and Fuels SPA team, which includes both national office and research station representation, works to improve program integration, enhance cross-station and interagency cooperation, and increase visibility of Forest Service R&D programs with partners and users.

At the field level, the research stations are rethinking their organizational structures to respond to changing issues and administrative realities. These efforts are in various stages of completion, but, in all cases, the SPAs are a significant factor in determining organizational structure, program content, and strategic direction. Wildland fire and fuels research will continue to be an important program area for all research stations for the foreseeable future.

## Strategic Planning

The overall goal of the R&D Wildland Fire and Fuels program is to "provide the knowledge and tools that managers use to reduce the negative impacts and enhance beneficial effects of fire and fire management on society and the environment." The strategic plan (USDA Forest Service 2006) provides a detailed framework for guiding the national program of fire-related R&D.

The Wildland Fire and Fuels R&D strategic plan is designed to maintain a solid basic research program, while addressing the short- and long-term needs of land managers and other clients and stakeholders. The plan supports the Forest Service and the U.S. Department of the Interior (DOI) national priorities of protecting communities from catastrophic wildland fire and improving and sustaining the resilience of wildland ecosystems. The plan also supports needs identified in the recent Committee on Environment, Natural Resources, and Sustainability task force report published by the Sub-Committee on Disaster Reduction of the President's National Science and Technology Council that outlined research and technology needs for reducing the impacts of major hazards, such as fire, on societies, economies, and natural resources.

## Wildland Fire and Fuels Strategic Plan

The 2006–2016 Forest Service Wildland Fire and Fuels R&D Strategic Plan (USDA Forest Service 2006) outlines three main activities for the program.

1. **Research.** Conduct basic and applied scientific research to enhance knowledge for use in developing the next generation of predictive and decisionmaking tools. Forest Service Wildland Fire and Fuels R&D teams will work with external partners to conduct research in four portfolios.
    a. **Core fire science:** physical fire processes, fire characteristics at multiple scales, and fire danger assessment.
    b. **Ecological and environmental fire science:** fire effects on ecosystem components and interactions between fire and the environment.
    c. **Social fire science:** public interactions with fire and fuels management, socioeconomic aspects of fire and fuels management, and organizational effectiveness.
    d. **Integrated fire and fuels management research:** management strategies and multiple scales, treatment and disturbance effects on ecosystem components, and harvesting and use of biomass removed for fuel reduction.
2. **Science Application.** Promote application of knowledge and tools by policymakers, wildland fire managers, and local communities. Work under this goal will ensure that knowledge generated by the Forest Service R&D is effectively transferred to user communities.
3. **Leadership.** Provide leadership for development and implementation of a nationally coordinated Wildland Fire and Fuels R&D program. Forest Service scientists and research leadership will strengthen collaborations with other agencies and partners to ensure that federally supported R&D programs are efficiently structured to reduce the negative impacts of wildland fire on people, property, and the environment, while working to improve the overall health of communities and the environment.

## Alignment With Forest Service and Interagency Strategic Plans and Goals

The agency's top management recognizes fire and fuels management as one of the Forest Service's most important resource issues. Fiscal year (FY) 2015 was the most expensive fire season on record. The Wildland Fire Management appropriation totaled more than $2.3 billion, which was 46 percent of the Forest Service's total discretionary appropriation in FY 2015. Fire suppression alone cost the Forest Service more than $1.7 billion in FY 2015. In FY 2016, the Wildland Fire Management appropriation represented more than 42 percent ($2.38 billion) of the Forest Service budget.

The Forest Service works closely with DOI, other Federal agencies, States, and tribal and local governments in fire management planning, in determining wildland fire R&D needs, and in the application of research results. Wildfire risk is one of the four threats identified by the Chief of the Forest Service. The R&D Wildland Fire and Fuels program aligns closely with Forest Service national goals, as outlined in the Forest Service strategic plan and other documents.

Forest Service wildland fire and fuels R&D aligns most closely with the current *Forest Service Strategic Plan (2015–2020)* Goal 1: Sustain Our Nation's Forests and Grasslands (http://www.fs.fed.us/sites/default/files/strategic-plan%5b2%5d-6_17_15_revised.pdf) and with the two strategic objectives—A. Foster resilient, adaptive ecosystems to mitigate climate change, and B. Mitigate wildfire risk. Wildland fire and fuels R&D also contributes to other strategic plan goals of conserving open space, providing abundant clean water, strengthening communities, delivering knowledge globally, and connecting people to the outdoors.

A number of other national planning documents support the need for an active R&D Wildland Fire and Fuels program in the Forest Service. These documents include *The National Cohesive Wildland Fire Management Strategy* (USDA and DOI 2014a), a strategic initiative to work collaboratively among all stakeholders and across all landscapes, using best science, to make meaningful progress toward three main goals: (1) resilient landscapes, (2) fire-adapted communities, and (3) safe and effective wildfire response.

In 2014, the Forest Service and DOI completed a joint assessment of their wildland fire management programs. This *2014 Quadrennial Fire Review Final Report* (USDA and DOI 2014b) sought to identify and explore key wildland fire management issues in the United States; assess the efficacy of current policy, strategy, and programs in expected future environments; and present a set of related actions for consideration by Federal wildland fire leaders at the Forest Service and DOI. The 2014 quadrennial fire review (QFR) process included a "baseline assessment" focused on four key issue areas (changing climatic conditions, risk management, workforce, and operational capabilities), development of four plausible alternative futures set in 2034 and related insights, and distillation of eight strategic-level conclusions and actions for consideration by fire leaders. Wildland fire and fuels R&D has a role in helping managers address each of these key issues.

### Implementation of the Strategic Plan

The Wildland Fire and Fuels R&D Strategic Plan was approved by the Forest Service Research Executive Team (FSRET)—which includes research station directors, Washington Office staff directors, and the Deputy Chief and Associate Deputy Chief for Forest Service R&D—in the fall of 2005. The responsibility for leadership in the implementation process rests largely with the national Wildland Fire and Fuels SPA team and its executive co-leads (the staff director for Forest Management Science in the Washington Office and the station director for the Rocky Mountain Research Station). The Wildland Fire and Fuels SPA team includes representatives from Washington Office R&D staffs, an ad hoc representative from Fire and Aviation Management, and a representative (typically an assistant station director or program manager) from each of the research stations. It is currently led by the national program leader for wildland fire and fuels R&D. For purposes of internal program management and coordination, we define five national portfolios, which include the four science areas described in the strategic plan and also science application. As part of the implementation process, FSRET approved the establishment of five national portfolio teams to foster coordination within and across research stations. The function of these teams is to evaluate existing programs and capacity, build voluntary internal and external collaboration, and make recommendations on improved program coordination and on program direction and capacity needs to the national Wildland Fire and Fuels SPA team and, through them, to FSRET. These teams include representation (typically at the scientist, team leader, or project leader level) from all research stations and also staff liaisons from the national SPA team. SPA and portfolio teams were established in the fall of 2005 and had their first joint planning meeting in January 2006. Portfolio teams have been working across research stations to describe the current program, identify current capacity and capacity needs, enhance cross-station collaboration, identify and support key partnerships, and develop recommendations for future program direction in the context of the strategic plan. Portfolio teams have also worked with the SPA team in identifying emerging issues and challenges for wildland fire and fuels R&D.

In 2014, R&D Wildland Fire and Fuels program managers recognized the need for a more strategic approach to planning and implementing the program in the face of the emerging needs for new information and tools. Building on desired outcomes identified by the fire management community, a group of scientists and other interested parties updated the Wildland Fire and Fuels R&D strategy (http://www.fs.fed.us/research/pdf/2006-10-20-wildland-book.pdf). This document has the vision for the future that science, technology, and policy will support management activities to protect life, property, infrastructure, and resources from the adverse effects of wildland fire; to protect the range of other values at risk; and to enhance the positive role fire plays in resource management. The previous strategic document has been the main guidance of Forest Service R&D related to wildland fire and fuels research for the past 10 years.

## Accomplishments and Outcomes

A substantial investment is made each year in Forest Service R&D to advance the knowledge and tools practitioners and managers rely on to establish and maintain resilient landscapes, promote fire-adapted communities, and safely and effectively respond to wildfires. Understanding the effect of this research is different than counting publications, presentations, and training sessions, and reporting quantitative performance metrics and highlights. Although these absolutes are important, it is also important to be able to define how the history of Forest Service wildland fire and fuels R&D has transformed the organizations that rely on it. The intention for this report is to provide detailed narratives about how sequential cumulative knowledge and applications from across all the components of the R&D Wildland Fire and Fuels program led to five transformational outcomes in the way the business of wildland fire is conducted in the United States and globally.

# Enhanced Physical Fire Science

**Wildland fire managers and responders are able to predict the occurrence, extent, and severity of fires with more precision and accuracy, resulting in better decisionmaking, resource allocation, and firefighter and public safety. National systems that characterize fire danger and risk are maintained and innovated.**

OUTCOME

1

## Fundamental Wildland Fire Processes

The rate of burning and intensity of wildland fires is strongly influenced by weather, topography, and a wide array of fuel characteristics. Developing, improving, and validating operational fire behavior models depend on laboratory studies and measurements from fires in controlled conditions. A credible, scientific approach requires that detailed experiments be performed in a controllable laboratory environment or in a well-defined in situ controlled burn.

The Forest Service has active laboratory research programs in multiscale, physical processes that govern fire behavior, including combustion processes, heat and energy transfer processes, dynamics in complex fuelbeds and environments, and fire-fuel-atmosphere interactions. Forest Service facilities (e.g., burn chambers) at the Missoula Fire Sciences Laboratory and the Forest Products Laboratory and partners' facilities at the National Institute of Standards and Technology (NIST) and the Insurance Institute for Business and Home Safety (IBHS) allow for safe, highly instrumented burns in laboratory conditions. Notable examples of Forest Service R&D laboratory-based experiments in fundamental wildland fire processes include measuring combustion in live and dead fuels (McAllister 2013, Pickett et al. 2010, Yashwanth et al. 2015); quantifying heat transfer to predict injury to trees (Chatziefstratiou et al. 2013); discriminating between radiant and convective heat transfer (Cohen and Finney 2010, Finney et al. 2015); defining complex fuel characteristics across landscapes (McAllister and Finney 2013, Pierce et al. 2009, Prichard et al. 2013, Rollins 2009, Ryan and Opperman 2013); measuring the ignitability and flammability of materials used in building construction (Hasburgh et al. 2015, White and Sumathipala 2013); and examining the role of seasonal live fuel foliar chemistry variations on fuel properties, flammability, and expected fire behavior (Jolly et al. 2014, McAllister et al. 2012).

Integrated in situ measurements of actual wildland fires across spatial scales are a necessary complement to laboratory experiments when moving toward the development of an operational fire behavior prediction application. The Prescribed Fire Combustion and

Atmospheric Dynamics Research Experiment (RxCADRE; http://www.firelab.org/project/rxcadre-project) is an exemplar of these types of measurements and is led by Forest Service wildland fire scientists. Funded through the Joint Fire Science Program (JFSP), RxCADRE targeted critical data needs outlined by members of the fire modeling community and involved more than 90 scientists and technicians. RxCADRE provides a high-quality, integrated wildland fire database based on surface, tower, and airborne measurements for 20 experimental fires ranging in scale from 4 to 4,000 acres. A special issue of the *International Journal of Wildland Fire* was dedicated to RxCADRE in 2016 (Peterson and Hardy 2016), and follow-on research and development will be supported in the future by the JFSP through the Fire and Smoke Model Evaluation Experiment (FASMEE; http://www.fasmee.net ). Other examples of in situ measurements of wildland fire for model development, enhancement, and validation include measurements of convective and radiant heat flux across gradients in the wildland fire environment (Butler 2010, Frankman et al. 2012, Kremens and Dickenson 2015) and measurements of fire weather and wind patterns (Cannon et al. 2014, Heilman et al. 2015). Much of this work is conducted with the objectives of building the next generation of fire behavior models, which are envisioned to integrate a cohesive, physics-based theory of wildland fire spread based on laboratory experiments and in situ measurements from wildland fires (Finney et al. 2012).

## Predicting Wildland Fire Behavior

Applications that integrate data characterizing topography, vegetation (fuels), and weather across landscapes with models that predict fire behavior are important tools used for wildland fire management and response. These applications are used to (1) predict fire behavior and effects, (2) assess wildfire risk and enhance situational awareness, and (3) design and compare fuel treatment projects and their effectiveness. Operational fire behavior applications are under constant improvement by Forest Service R&D and their partners as new discoveries are made about the fundamental physics of wildland fire. Current models do not accurately reflect the complexity of combustion processes, the temporally and spatially variable biophysical environment in which they occur, the complexity of wildland fuels, or interactions between fire and the atmosphere. As a result, predictions are sometimes incomplete or inaccurate in ways that can negatively affect fire planning and response. Recent and ongoing Forest Service research on basic understanding of fundamental physical fire processes and interactions among fire, topography, and weather is focused on development of a next generation of innovative predictive tools and decision-support systems for wildland fire management and response. This new capacity is intended to enhance situational awareness and safety for firefighters, public safety, landscape resilience, and environmental quality.

During the past several decades, the use of mathematical models to predict fire behavior has played an important supporting role in wildland fire management and response. When used in conjunction with personal fire experience, these predictions may be applied to a range of fire management activities, including wildfire behavior prediction, prescribed fire planning and implementation, and fuels assessments. The BehavePlus fire behavior prediction and fuel modeling system (Andrews 2014) was among the early computer systems developed for wildland fire management that integrated the suite of mathematical models relevant to wildland fire predictions. BehavePlus is in its fifth version and is widely used today. BehavePlus includes more than 40 fire models and provides a means of modeling fire behavior (such as rate of spread and spotting distance), fire effects (such as scorch height and tree mortality), and the fire environment (such as fuel moisture and wind adjustment factor). Although more recent spatially explicit systems include many of the base models included in BehavePlus, a need remains for point-based predictions for many fire management applications, such as prescribed fire planning and predicting fine-scale fire behavior during ongoing fires. BehavePlus also serves as a valuable learning tool, because an understanding of the models included in BehavePlus improves interpretation of the results of the spatial system in which the specific modeling that occurs at each spatial element is less evident (Andrews 2014).

The spatially explicit modeling of wildland fire across landscapes was initially constrained by computing limitations, lack of comprehensive geospatial data, and required refinements in mathematical models. After these constraints were largely removed by the late 1990s and early 2000s, spatial implementation of fire behavior and effects models was possible was and accessible to most land managers. These models include FARSITE, FlamMap, and FSPro.

The FARSITE fire area simulator (Finney 2004) models fire growth under conditions that vary in both space and time. The fire behavior at a point (pixel) depends on the fire spreading from adjoining pixels and the conditions at the time it burned. The FlamMap fire mapping and analysis system (Finney 2006) calculates fire behavior for each point on a landscape with fuel moisture and wind constant in time. For the basic FlamMap operation, each calculation is independent of its neighbors. FlamMap also includes the ability to calculate minimum travel times for fire spread, which is useful in determining effective strategic fuel treatment locations and restoration activities (Ager et al. 2012). The FSPro fire spread probability system developed at the Forest Service Missoula Fire Sciences Laboratory performs hundreds or thousands of separate fire growth simulations from weather sequences based on forecasts or scenarios (Hollingsworth et al 2012). While FARSITE predicts a fire perimeter location, FSPro produces the probability of the fire reaching each point from the known fire perimeter during the specified simulation duration (such as 2 weeks).

New applications being developed by Forest Service scientists focus on the incorporation of new discoveries about the fundamental physics of wildland fire behavior; the incorporation of new measurement technologies; and three-dimensional measurements that characterize the structure, composition, and condition of wildland fuels. In 2008, Forest Service R&D leaders in fundamental physical fire science developed a strategic framework focused on increasing coordination and collaboration in fire behavior research and development and on expediting future fundamental fire science activities toward a new, comprehensive fire model (Hardy et al. 2008). Work at the Pacific Wildland Fire Sciences Laboratory includes the enhancement and evaluation of a coupled fire-atmosphere model based on the principles of computational fluid dynamics called the Wildland-Urban Interface Fire Dynamics Simulator (WFDS). WFDS is an example of physics-based process models; it represents the next-generation, physics-based applications that model combustion processes and fire behavior in both wildland and mixed urban interface fire environments at a variety of spatial and temporal scales (Hoffman et al. 2015, Mell et al. 2010, Parsons et al. 2011). At the Missoula Fire Sciences Laboratory, extensive laboratory-based and in situ experiments are underway to characterize the fundamental processes that influence flame spread, buoyant instabilities in flaming fronts, and convective heat transfer (Finney et al. 2015). The intention is that development of next-generation fire behavior models will decrease uncertainty when wildland fire managers and responders are (1) predicting fire behavior and effects; (2) assessing wildfire risk and enhancing situational awareness; and (3) investing in, designing, and evaluating fuel treatment projects.

## Wildfire Danger, Potential, and Risk Assessment

Fire danger rating provides information useful for all aspects of fire management, including preventing, suppressing, and managing wildfires. Wildland fire managers consider fire danger when making decisions regarding personnel levels, contingency resources, prepositioning of firefighting equipment, and resource response to new fires. Forests may be closed for public recreation when fire danger is extreme. Fire suppression funding is based in part on the level of fire danger. A constant need exists to improve methods for assessing seasonal fire danger and developing tools to support specific fire management needs. Current research is focused on improving fire and fuel moisture models that form the basis for fire danger rating, spatial modeling techniques, and weather modeling (Freeborn et al. 2015; Holden and Jolly 2011; Jolly et al. 2010, 2015). Forest Service R&D is also leading the effort to modernize the U.S. National Fire Danger Rating System in cooperation with the National Wildfire Coordinating Group and interagency partners. This effort is the first science-based revision to the system in nearly 40 years.

In recent years, Forest Service R&D has integrated state-of-the-art fire behavior models with new fuel classifications and maps to develop geospatial data and decision-support systems that enable wildland fire managers and responders to efficiently invest in risk mitigation and landscape restoration projects, maintain situational awareness and safety during wildfires, and work with property owners and communities to understand wildfire risk in their own landscapes. One such product is the wildfire hazard potential (WHP) map, a geospatial product produced by Forest Service R&D that helps to inform evaluations of wildfire risk or prioritization of fuels management needs across very large landscapes (millions of acres; Dillon et al. 2015). The specific purpose for the WHP map is to represent the potential for wildfires that would be difficult to suppress. The WHP map is developed using spatial estimates of wildfire likelihood and intensity generated with the Large Fire Simulator (FSim; Hollingsworth and Menakis 2011) and also spatial fuels and vegetation data from LANDFIRE 2010 and point locations of fire occurrence from Fire Program Analysis (ca. 1992 to 2012). Areas mapped with higher WHP values represent fuels with a higher probability of experiencing torching, crowning, and other forms of extreme fire behavior under conducive weather conditions (Dillon et al. 2015).

The Wildland Fire Assessment System (WFAS), maintained by Forest Service R&D, is an integrated, Web-based resource to support fire management decisions that is updated daily with national wildland fire conditions and maintained to include the most recent advances in fire danger rating (Jolly et al. 2005). It has an extensive nationwide user base of Federal, State, tribal, and local land managers. The system provides multitemporal and multispatial views of fire weather and fire potential, including fuel moistures and fire danger classes from the U.S. National Fire Danger Rating System, Keetch-Byram and Palmer drought indices, lower atmospheric stability, and satellite-derived vegetation conditions. It also provides fire potential forecasts from 24 hours to 30 days. Point data for many products are provided in addition to spatial data for more localized applications. WFAS is constantly under revision to refine existing products and to increase the utility of more spatial data products, such as gridded surface meteorology and newly available satellite data. Many of these new products incorporate Internet mapping services to enable users to resolve spatial products to a region of interest. These revisions also provide higher resolution data for regional and local applications with higher spatial and temporal resolution. Planned changes will support decisions made at national, regional, and local levels (Jolly et al. 2005). WFAS is one of the only systems of its kind that integrates widely disparate databases relevant to wildland fire managers. It provides multitemporal and multispatial assessments of fire weather, fire potential, and the condition of live vegetation across broad spatial scales.

Forest Service R&D has developed the Wildland Fire Decision Support System (WFDSS; Calkin et al. 2011b, Noonan-Wright et al. 2011) to support risk-informed decisionmaking for wildland fires in the United States. WFDSS integrates national weather data and forecasts, fire behavior prediction, economic assessments, smoke management assessments, and landscape databases to efficiently formulate and apply information to the decisionmaking process. Risk-informed decisionmaking is becoming increasingly important as a means of improving fire management and offers substantial opportunities to benefit natural and community resource protection, management response effectiveness, firefighter resource use and exposure, and, possibly, suppression costs (Noonan-Wright et al. 2011).

During the past 5 years, the Forest Service has made great advances in capacity to manage wildfire risk according to standards and guides derived from risk and decision science. Forest Service R&D has fostered a capability to approach wildland fire management problems in the context of risk-based decisionmaking science and technology. It is clear, however, that, given the growing complexities that all organizations (including the agency's Federal partners, State partners, and other stakeholders—both public and private) face, that much yet needs to be accomplished to develop an integrated risk-management framework that serves a number of needs and purposes focused on the vision of Americans living with wildland fire. This framework must be capable of operating across a range of organization and stakeholder types, and it cannot be isolated to the needs and functions of a single organization. That is, the framework must serve to bind together the various entities involved in managing risk in today's complex sociopolitical context, in which landscape-scale problems are distributed across multiple jurisdictions and stakeholders.

## OUTCOME 2

# Better Access to Smoke and Emissions Tools

**Practitioners and regulators have access to information and tools for estimating smoke and emissions from wildland fire to support decisions about suppression, managed wildfires, and prescribed fire implementation, primarily to address firefighter and public health and safety.**

## Atmospheric Chemistry

Wildland fires are a major source of atmospheric pollutants and greenhouse gases. Fires emit four of the six U.S. Environmental Protection Agency (EPA) criteria pollutants (carbon monoxide, nitrogen oxide, particulate matter, and sulfur dioxide), and they also emit hydrocarbons and oxygenated volatile organic compounds, which are precursors of ozone and secondary fine particulate matter. Under current provisions of the Clean Air Act, States must institute management programs to reduce pollutant emissions to meet National Ambient Air Quality Standards (NAAQS) for ozone and PM$_{2.5}$ (particles with a diameter smaller than 2.5 micrometers). The EPA's Regional Haze Rule mandates States to reduce regional haze, and recent NAAQS standards for PM$_{2.5}$ (the 24-hour standard was reduced from 65 to 35 micrograms per meter cubed) will increase the demands on the Forest Service and other public land management agencies to address the air quality impacts of emissions from wildfires under full suppression, managed wildfires, and prescribed fires. On a global scale, fires influence tropospheric chemistry. Biomass burning impacts the global climate through the emission of greenhouse gases. Furthermore, smoke aerosols from biomass burning can have a significant direct impact on regional radiative forcing, which affects long-term weather patterns.

Active research programs across Forest Service R&D are assessing the impact of wildland fires on air quality and global environment by developing accurate estimates of fire emissions and smoke plume dispersion (Hao and Larkin 2014, Heilman et al. 2014, Larkin et al. 2014, Urbanski et al. 2011). The objectives of this interdisciplinary research are to quantify the emissions from biomass fires in different ecosystems and to characterize smoke plume dynamics and resultant changes to the atmosphere from wildland fires. It is important to note here that accurately estimating emissions and smoke transport from wildland fires depends on fire behavior models and fuel characterization described in other sections of this report. To address the need for estimating emissions and smoke transport, Forest Service scientists are conducting large-scale ground-based and airborne field sampling to quantify emissions from wildland fires across the United States and globally (e.g., Evangeliou et al. 2016, McRae et al. 2009, Strand et al. 2016). In parallel laboratory combustion chamber experiments, scientists study the dependence of trace gas and $PM_{2.5}$ emissions and particle size distributions on fuel characteristics and during combustion (e.g., smoldering versus flaming). Smoke plume heights and dynamics are investigated by theoretical modeling, in situ monitoring by using state-of-the-art LiDAR (Light Detection and Ranging), and aerial imaging (Kovalev et al. 2015, Lee et al. 2010).

One example of this research is the development of an automated system for quantifying the emission rates of atmospheric pollutants and greenhouse gases from wildfires in near-real time with a 1-square-kilometer resolution in the contiguous United States. In addition, an automated system for retrieving and processing LiDAR data has been developed to provide three-dimensional distribution and the dynamic processes of smoke plumes in real time (Kovalev et al. 2015). Theoretical advances in fire plume dynamics have provided better prediction of plume characteristics for large fires, and LiDAR measurements provide useful data that describe the vertical profiles of aerosol particles in smoke plumes.

## Smoke Transport Modeling

Smoke from wildland fires is a significant air quality issue impacting human health, the quality of life, and the economic well-being of many communities every year. NAAQS attempt to regulate and limit the health impacts of fine particulates, and the Regional Haze Rule addresses visibility in wilderness areas and large national parks. Although current air quality regulations related to smoke from wildland fires emphasize $PM_{2.5}$ as the element of concern, there is growing awareness of the importance of wildland fires for atmospheric mercury, ozone, methane, and other chemical species. As land managers work to decrease the risk of catastrophic wildfire and restore ecosystem health, air quality regulations and public health concerns increasingly limit their ability to establish and maintain resilient landscapes and mitigate wildfire risk through the use of prescribed fire. Land managers and air quality regulatory personnel need accurate, timely information regarding fire emissions and how the impacts of smoke can be predicted, planned for, and managed.

Smoke transport and dispersion depend on the three-dimensional structure of the atmosphere, terrain, and fire intensity. Forest Service scientists use a combination of theory, physical and statistical models, satellite data, and field measurements to learn how smoke from wildfires spreads across the land and vertically through the atmosphere (Cunningham and Goodrick 2013, Goodrick et al. 2012). To forecast smoke transport from wildland fires, scientists use models that calculate fire emissions, plume characteristics, atmospheric smoke dispersion, and trajectories. Each model has different strengths and weaknesses. For example, a number of atmospheric dispersion models are currently available, each originally designed to meet needs other than wildland fire. These models must be carefully evaluated and tested to ensure they are valid when applied for smoke transport and at appropriate scales. Different user needs also require different modeling approaches. The BlueSky smoke modeling system (Larkin et al. 2009), for example, is aimed at the needs of the smoke management community, but the Weather Research and Forecasting and Chemistry (WRF-Chem) and Congestion Mitigation and Air Quality Improvement (CMAQ) smoke forecasting models are targeted at addressing specific questions related more broadly to air quality (Achtemeier et al. 2011, Lei et al. 2010). Results of Forest Service research have also affected the broader smoke management and regulatory community through collaborations with other Federal, State, and tribal agencies and internationally. Direct comparisons among similar models are possible, and evaluation of the choice of these models on the accuracy of smoke predictions can help identify knowledge gaps. The result is faster, more directed improvement of underlying science. The ongoing FASMEE project (http://www.fasmee.net), an effort led by the Forest Service in cooperation with the U.S. Department of the Interior, EPA, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and the U.S. Department of Defense, will provide advanced measurements necessary to evaluate and advance operationally used fire and smoke modeling systems and their underlying scientific models. The field campaign will be conducted on large operational prescribed fires targeting heavy fuel loads and burned to produce high-intensity fires with developed plumes in the Southeastern and Western United States.

Daily real-time smoke predictions are available nationally through the BlueSky smoke prediction system (http://www.airfire/topics/smoke; Larkin et al. 2009). Users can see the smoke impacts of both wildfire and prescribed fires. The National Weather Service's Smoke Forecast Product uses fire emissions generated by BlueSky, as does the Canadian BlueSky system. Smoke transport models are integrated into the Wildland Fire

Decision Support System wildfire risk assessment platform (Larkin et al. 2010), and a new approach relies on information from social media to estimate smoke transport from wildfires (Sachdeva et al. 2016).

The importance of accurate estimates of smoke and emissions must not be underemphasized because they may have acute and chronic effects on firefighter and public health (Adetona et al. 2014, McCaffrey and Olsen 2012, Preisler et al. 2015). To assist in operational smoke and air-quality estimates from individual wildfires, Forest Service R&D has collaborated with Fire and Aviation Management to create a new Air Resource Advisor position in the incident command structure.

Smoke and air-quality information has an important role in wildland fire decisionmaking that is reinforced in the 2009 *Guidance for Implementation of Federal Wildland Fire Management Policy*. A key intent of the guidance is to allow for consideration and use of the full range of strategic and tactical options that are available in the response to every wildland fire. This guidance directs that wildland fire responses will be developed through evaluations of situational assessment and analysis of hazards and risk. It also defines implementation actions and directs documentation of decisions and rationale. Smoke and air quality are now among the top issues in decisionmaking, both on wildfires under full suppression, managed wildfires, and prescribed fires (Larkin et al. 2010). During the past several years, the Joint Fire Science Program has had an active line of work investigating smoke and emissions (see http://www.firescience.gov for more information).

# Advanced Wildland Fuels Management

## OUTCOME 3

**Wildland fuels are characterized using consistent and comprehensive science and technology to meet diverse objectives and ensure effective investment strategies to restore resilient landscapes, mitigate wildfire risk, and deliver benefits to the public.**

## Characterizing Wildland Fuels

Characterizations of wildland fuels are required as inputs into wildland fire management applications that predict fire behavior, estimate smoke transport and emissions, evaluate the effects of fire at multiple scales, and quantify wildfire risk. Wildland fuelbeds are complex, consisting of diverse components that are composed of particles of many sizes, types, densities, and shapes distributed horizontally and vertically through vegetation communities (Keane 2015). Further, these characteristics are highly variable across spatial and temporal scales (Keane et al. 2012). This extreme level of complexity has required novel and diverse approaches to accurately measure, describe, classify, and eventually map wildland fuels, and this complexity has resulted in simplified, generalized descriptions of wildland fuelbeds for inputs in many wildland fire management applications (for example, see the fire behavior fuel models of Anderson (1982); the revised fire behavior fuel models of Scott and Burgan (2005); and the fuel loading models of Lutes et al. (2009). Worldwide, Forest Service scientists work together to address the challenges of quantifying wildland fuels by evaluating and implementing novel approaches for developing and improving fuel characterization systems and by researching innovative ways to characterize wildland fuels for input to the next generation of wildland fire management applications (Keane 2013, Parsons 2006). The overall objective has been to develop user-inspired systems that reduce uncertainties in the estimates of critical wildland fire issues, such as extreme fire behavior, the effects of wildland fires on landscapes, characterization of carbon stocks, and mitigation of wildfire risk to resources and human communities.

Fuel composition, structure, and condition often constrain opportunities for mitigating risk through hazardous fuel reduction and fire suppression. Fuel classifications and maps have provided essentially two-dimensional or single-layer fuel characteristics, but we now know that wildland fuel properties vary widely in their three-dimensional structure across multiple spatial scales, which influences wildland fire behavior, smoke and emissions, and effects on landscapes (Keane et al. 2012, Parsons et al. 2010). Traditional fuel classifications do not adequately represent the diversity in the structure of wildland fuels, and they contain insufficient information for precise estimates of emissions and implementing fuel management and landscape restoration activities (for example, Andersen 1982, Scott and Burgan 2005). One approach developed by Forest Service R&D, the Fuel Characteristic Classification System (FCCS), enables land managers, regulators, and scientists to efficiently create and catalog fuelbeds and classify them according to potential fire behavior (rate of spread, flame length, reaction intensity, and potential effects) and relative fire hazard (McKenzie et al. 2012, Prichard et al. 2013). FCCS was designed to enable users to choose among fuelbeds from a comprehensive library or create their own custom fuelbeds. In addition to building fuelbeds, FCCS calculates (1) potential indices of surface fire behavior, crown fire, and available fuel on a scale from 0 to 9 for each fuelbed; (2) rate of spread, flame length, and reaction intensity under benchmark and user-specified environmental conditions by using a reformulated Rothermel (1972) surface fire behavior model; and (3) a suggested fire behavior fuel model for input into existing fire behavior models (Andersen 1982, Scott and Burgan 2005). Another fuel classification system, Fuel Loading Models (FLMs), developed by Forest Service R&D for mapping, uses measurements of surface fuel loadings to discriminate between classification categories across a landscape or project area to specifically simulate emissions and maximum soil temperatures with the least uncertainty (Lutes et al. 2009). Both FCCS and FLMs can be mapped across large regions because they are correlated to other mapped biophysical attributes such as existing vegetation composition and structure, precipitation, and other landscape attributes, such as net primary productivity (Rollins 2009, Ryan and Opperman 2013). Heterogeneity in fuel composition and structure, however, occur at finer spatial scales than current, comprehensive regional-to-national mapping technologies (Keane et al. 2015).

Extreme fire behavior spreading through forest canopies (i.e., crown fires) is a chief concern among many wildland fire managers in the United States because it has increased in frequency, intensity, and size in many areas, specifically in the Western United States. Compared with surface fires, crown fires are responsible for dramatic increases in smoke and emissions, greater and longer lasting ecological damage (e.g., higher plant mortality, increased soil mineralization, and adverse changes to water quality and supply), greater risk to firefighters and the public, and increased risk of property and infrastructure loss. Forest Service R&D uses four canopy characteristics that govern the transition of surface fires to crown fires: (1) canopy base height (height of the bottom of the live canopy from the ground surface), (2) canopy bulk density (mass per unit volume of combustible crown biomass, including foliage, twigs, and fine branches), (3) canopy height (average height of the dominant tree strata in a stand), and (4) canopy closure (percent vertically projected canopy cover in the stand). A number of wildland fire management applications require estimates of these canopy fuel characteristics to accurately simulate crown fires (Finney 2004, Reinhardt et al. 2006b). Forest Service scientists and partners have worked to develop comprehensive descriptions, measurement techniques, and maps of canopy fuel characteristics for wildland fire management, resulting in more accurate estimates of crown fuels across the United States (Contreras et al. 2012, Ex et al. 2015, Kramer et al. 2014, Reeves et al. 2009, Ryan and Opperman 2013, Werth et al. 2016).

The LANDFIRE Program (http://www.landfire.gov), led by scientists from the Forest Service, U.S. Geological Survey (USGS), and The Nature Conservancy, is a multistakeholder project (including States, tribal governments, and nongovernmental organizations) that develops consistent and comprehensive maps and data describing vegetation, wildland fuel, fire regimes, and ecological departure from historical conditions for fire management across the United States (Rollins 2009, Ryan and Opperman 2013). It is a shared project between wildland fire management and research and development programs of the Forest Service and the U.S. Department of the Interior (DOI). LANDFIRE meets wildland fire management and response needs for comprehensive, integrated data to support landscape-level fire management planning and prioritization, wildfire response activities, community and firefighter safety, effective resource allocation, and collaboration between agencies and the public. LANDFIRE data products are created as 30-meter raster grids and are available at http://www.landfire.gov. LANDFIRE data products are updated every 2 years and have been institutionalized as the primary data source for modeling activities aimed at meeting the goals of the United States' National Cohesive Wildland Fire Management Strategy, wildland fire decision support, and wildland fire risk assessments. Moreover, LANDFIRE products have been cited more than 2,100 times in the peer-reviewed literature, validating its extensive use in a wide variety of research and management projects.

## Improving Characterization of Wildland Fuels

Creating comprehensive and consistent fuel description systems requires a full understanding of the ecology of wildland fuels. Forest Service scientists investigate processes that control fuel dynamics, such as biomass production, deposition, decomposition, and accumulation to understand how fuel characteristics change over time and space (Jolly et al. 2012b, Keane 2013, Keane 2015). Science and technology that quantify the chemistry and morphology of fuel elements throughout the vegetation profile are required to completely describe, classify, and map wildland fuels for current and future uses (Parsons et al. 2010). Spatial distributions of different fuel components and properties must be described so that the appropriate sampling methods can be used or developed to estimate needed fuel properties with minimal bias (Keane et al. 2012), and the appropriate mapping techniques and technologies have to be designed to match the scales of fuel variation (Keane et al. 2013). While the next generation of fire behavior and effects simulation models is being developed, it is critical that new fuel classification systems be built to balance ecological understanding of fuel dynamics with the new input model requirements. These requirements will allow for the input of information that reflects dynamic quality and spatial variation of fuel properties that account for current and future fire behavior inputs such as kinetics, morphology, and spatial distribution (Parsons et al. 2010). Fuel description systems for these three-dimensional fire models will be completely different from current fuel models, because they must contain information on diverse chemical and physical fuel characteristics such as bulk density, surface-area-to-volume ratio, moisture content, lignin fraction over multiple spatial (e.g., clumpiness, pattern, variability) and time scales (e.g., changes in particle density due to decomposition) for various fuel characterizations (i.e., shape, size, volume). Each of these characteristics must have an associated sampling method for accurate quantification, and these methods must account for the wide diversity of fuel particles comprising the fuelbed (Keane et al. 2013, Riccardi et al. 2007).

Innovative sampling techniques must balance the spatial resolution needed by fire models with accuracy needed by other fuel applications, such as estimating smoke emissions, carbon inventories, and smoldering combustion, for both research and management. Development of new comprehensive fuel classifications will need high-quality data across large geographical areas, diverse ecosystems, and complex fuelbeds (Lutes et al. 2009). New inventory techniques developed from basic wildland fuel ecological research can be integrated for this effort, along with the information needed to convert legacy fuels data to newer formats. Geo-referenced fuels inventory data are important not only for classification development but also for map creation and validation; simulation model initialization and parameterization; and fuel treatment planning, implementation, and monitoring (Keane 2015, Reeves et al. 2009).

The Forest Service R&D's Forest Inventory and Analysis program is now collecting critical fuel information in many parts of the United States, which represents a significant step forward in developing comprehensive fuel datasets for future fire management applications (Wang et al. 2013). To provide wildland fire management fuel description systems for the next generation of fire applications, any new system should look to future science and technology. It will be more efficient and effective to design new and innovative fuel-characterization systems in concert with the scientists developing the next-generation fire-modeling applications than to continue modifying existing fuel-classification systems as new fire science technologies are developed (Keane 2015, Keane et al. 2013).

## Fuel Treatment Effectiveness

The effectiveness of active fire management to manipulate wildland fuels for a variety of objectives has been a key focus area for Forest Service R&D for many years. Common fuel management objectives include—

- Reducing the risk of undesired and potentially dangerous wildfire behavior.
- Providing strategic opportunities for wildfire suppression and management.
- Reducing wildfire risks to firefighters, communities, and residents of the United States.
- Restoring and maintaining resilient and productive landscapes and ecosystems.
- Reducing damage that occurs after wildfires.
- Limiting the spread of invasive species and detrimental pathogens.

Meeting the Forest Service's goals for sustaining resilient landscapes, mitigating wildfire risk, and delivering benefits to the public (USDA Forest Service 2015a) where wildfires have been an important historical ecosystem process demands integrated planning and active management based on sound, user-inspired ecological, physical, and social science and its resultant technologies. Knowledge and applications developed by Forest Service scientists and partners across the portfolios of the Forest Service Fire and Fuels R&D program (USDA Forest Service 2006) provide the foundation for integrated approaches to planning active management of wildland fuels. Years of Forest Service R&D have become implicit in wildland fire management activities focused on incorporating information on contemporary and future environmental and land use changes to the composition, structure, and function of landscapes and the socioeconomic context when planning fuel treatments (Reynolds et al. 2013, Smith 2012). To continue to innovate, Forest Service R&D scientists and partners focus on evaluating the effectiveness and tradeoffs between different fuel treatment approaches, and they actively measure, model, and monitor the interacting effects of changing baseline conditions, natural disturbances, land use, and the socioeconomic environment at multiple scales across the United States (Zimmerman et al. 2014).

Forest Service scientists investigating active management that alters wildland fuels have measured and modeled the effectiveness of mechanical treatments, prescribed fire, and managed wildfires for restoring and maintaining healthy, resilient, fire-adapted landscapes and human communities while also evaluating the changing characteristics of fire regimes and climate over medium to long periods of time (Keane 2015). In addition, scientists with Forest Service R&D have made great strides in improving ways to improve the efficiency of biomass harvested for fuel reduction by developing new uses and better technologies for processing small-diameter biomass with the objective of increasing the economic incentives for active restoration and risk mitigation for communities in the wildland-urban interface (WUI; Livingston 2008, Morrow et al. 2013, Winandy et al. 2006, Zhu et al. 2016). Providing a foundation for ecologically sound, effective, and efficient management practices has required that scientists evaluate tradeoffs of alternative treatments on fire behavior and characteristics, fire effects, long-term landscape resilience and productivity, and delivery of benefits to the residents of the United States.

The costs of suppressing wildfires have dramatically increased in the past decade (USDA Forest Service 2015b), as have the size and complexity of wildfires (Calkin et al. 2015; Champ et al. 2013; Noonan-Wright and Opperman 2015; Ager et al. 2016). Much of the billions of dollars spent suppressing fires is spent in the WUI, where increasing rates of development into wildlands expose more homes and structures to abnormally intense wildfires (USDA and DOI 2014). The Forest Service has sought to reduce the rapidly rising costs of fighting wildfires by thinning forests and removing fuel in the WUI before a wildfire occurs. These fuel treatments have amounted to millions of acres treated at a cost of hundreds of millions of dollars during the past decade, but is this proactive approach having an effect? Research by Forest Service R&D scientists indicate that the answer is a qualified yes, as long as adaptive management and combinations of mechanical and prescribed fire are implemented over time. It is important to note, however, that treatments must focus on functional restoration of ecosystems across broad landscapes, otherwise treatment programs are likely to fail at meeting their objectives. It is impossible to catalog the hundreds of Forest Service publications on science and technology related to fuel treatment effectiveness here, but, for examples, see Ager et al. (2016), Charnley et al. (2015), Cochrane et al. (2012), Harrington (2008), Hood et al. (2015), Hudak et al. (2011), Miller et al. (2012), North et al. (2012), Parks et al. (2014, 2016), Pritchard et al. (2010), Schwilk et al. (2009), Thompson et al. (2013), and Vaillant et al. (2015).

Perhaps the broadest and most comprehensive study of fuel treatment effectiveness was the National Fire and Fire Surrogates Study (NFFS) supported by Forest Service R&D and the Joint Fire Science Program and led by scientists from Forest Service R&D, USGS, and numerous university partners (McIver et al. 2012, Schwilk et al. 2009). The 12-site NFFS was a multivariate experiment that evaluated landscape and ecological consequences of alternative fuel management treatments in seasonally dry forests of the United States. Each site was a replicated experiment with a common design that compared an unmanipulated control, a prescribed fire, a mechanical fire treatment, and a mechanical plus fire treatment. Variables within the vegetation, fuelbed, forest floor and soil, common insects, tree diseases, and wildlife were measured in 25-acre units, and ecological response was compared among treatments at the sites and across sites to better understand the influence of differential site conditions. For most sites, treated stands were predicted to be more resilient to wildfire if it occurred shortly after treatment, but, for most ecological variables, short-term response to treatments was subtle and transient. Most ecological factors were strongly site specific, suggesting that wildland fuel managers employ adaptive management at multiple scales. Mechanical treatments did not serve as surrogates for fire for most ecological factors, suggesting that wildland fire must be maintained whenever possible. Restoring and maintaining resilient landscapes will require repeated treatments over time, with eastern forests requiring more frequent applications (McIver et al. 2012, Schwilk et al. 2009). During the past several years, the Joint Fire Science Program has had an active line of work investigating fuel treatment effectiveness (see http://www.firescience.gov for more information).

## Fuels Treatment Decision Support

Land management organizations need consistent, science-based processes for analyzing where and when to place fuels treatments on a landscape while taking into consideration multiple resource and management objectives, and for measuring the effectiveness of those treatments in reducing undesired fire behavior and meeting the other fuel management objectives listed previously. Peterson et al. (2007) cataloged the myriad fire management models and applications available for decision support. To address the numerous and potentially overwhelming number of applications for fuels treatment decision support, the Joint Fire Science Program, DOI, and Forest Service R&D developed the Interagency Fuels Treatment Decision Support System (IFTDSS; https://iftdss.firenet.gov; JFSP 2009). Maintained by Forest Service R&D's Wildland Fire Management Research and Development Program, IFTDSS organizes wildland fuels planning data and applications into a seamless user environment. IFTDSS offers users access to powerful modeling software from within a well-designed, intuitive graphical user interface, and it provides a common platform for the further development of fuels-planning software tools. IFTDSS has revolutionized the way fuels planners do their jobs, because it simplifies the fuels treatment decision process by minimizing planners' struggles with unfamiliar models and databases that can be difficult to access and manipulate. IFTDSS has also made fuels treatment decisionmaking less time consuming, more scientifically rigorous, and easier to explain to stakeholders (JFSP 2009).

The Landscape Treatment Designer (LTD; http://www.fs.fed.us/wwetac/ltd; Ager et al. 2012) and ArcFuels (http://www.fs.fed.us/wwetac/arcfuels; Vaillant et al. 2013; Vaillant and Ager 2014) represent additional approaches to integrating applications to simplify strategic placement of fuels treatments and conducting risk assessments. The LTD spatially prioritizes and optimizes landscape-level treatments by developing scenarios for planning based on numerous landscape criteria. These scenarios enable fuel managers to explore geographically relevant landscape fuels treatment scenarios. The LTD uses inputs on spatial treatment objectives, activity constraints, and treatment thresholds, and then it identifies optimal fuels treatment locations with respect to the input parameters. The input data represent polygons that are attributed with information about expected fire behavior and the polygon's overall contribution to one or more landscape management objectives. The program can be used in a number of different ways to explore treatment priority and decision rules that manifest themselves on large (1 million hectares) landscapes as spatially explicit treatment strategies (Ager et al. 2012).

ArcFuels is a library of macros within the ArcMap GIS software. It links (1) key wildfire behavior models, (2) fuels and vegetation data, (3) Microsoft Office software, and (4) ArcGIS (http://www.esri.com). It is used in fuels treatment planning and wildfire risk analyses to streamline wildfire threat and mitigation assessments. The ArcMap framework helps specialists leverage local data and existing fire models to address project-specific issues that typify many fuels treatment projects. ArcFuels adds a spatial context to the Fire and Fuels Extension of the Forest Vegetation Simulator (FFE-FVS; Crookston and Dixon 2005, Reinhardt 2005) and facilitates its application for both stand and landscape modeling of fuels treatments, including estimating carbon budgets (Crookston et al. 2010, Vaillant and Ager 2014). The structure of ArcFuels provides users with a logical flow from stand-to-landscape analyses of vegetation, fuel, and fire behavior using a number of existing wildland fire behavior and effects models (Ager et al. 2012; Vaillant and Ager 2014).

Several other applications have found great use in fire management (Keane et al. 2015). The revision of two commonly used fuel applications—CONSUME (Ottmar et al. 1993), FOFEM (Reinhardt and Keane 1998), and FuelCalc (Reinhardt et al. 2006a)—has integrated all the fuel classifications (e.g., FCCS, FLM) into fire-effects prediction systems for fire planning (http://www.firelab.org). FOFEM version 6.0 and CONSUME now have revised fuel inputs to calculate first-order fire-effects, while FuelCalc version 1.0 now has the ability to implement silvicultural cuttings (e.g., thinning, pruning) and prescribed burning to change the surface and canopy fuel characteristics to reduce wildfire risk.

## OUTCOME 4

# Improved Social and Economic Context for Wildland Fire Management and Response

**The public is aware of the costs and benefits of wildland fire management and response, and socioeconomic research and development are foundations for large landscape collaboration, organizational performance and effectiveness, and firefighter and public safety. Fire management organizations have access to information and tools to improve performance through learning and innovative leadership.**

The growing number of people living in areas with high wildfire risk is an important factor contributing to the complexity of wildland fire management and response in the United States. Active involvement of the public in planning is essential to mitigating negative effects of wildfire (e.g., loss of property and infrastructure) while continuing to deliver public benefits by providing clean water, establishing and maintaining resilient human communities, and creating healthier and more resilient landscapes that provide the natural resources and ecosystems on which the public depends (McCaffrey 2015, USDA Forest Service 2015a). Federal, State, tribal, and local fire and land management organizations interact in a complex manner with communities to manage wildfires in an effort to reduce potential losses and increase potential benefits, develop and implement safe and effective responses to wildfires, and manage wildland fuels in and adjacent to those communities (i.e., the wildland-urban interface [WUI]). All these activities require balancing a wide range of monetary and nonmonetary considerations when assessing tradeoffs of different actions that cross multiple landscapes and jurisdictions.

Social fire science historically has been overshadowed by physical and ecological wildland fire science. Since 2001, however, the Forest Service R&D Wildland Fire and Fuels program has placed increasing emphasis on research that will (1) lead to a broader understanding of the interactions between wildland fire and fuels management and society, (2) increase understanding of the costs and benefits (monetary and nonmonetary) of wildland fire, (3) enable co-managing wildfire risk across ownerships and jurisdictional boundaries, and (4) inform efforts to improve firefighter and public safety and health and achieve effective and efficient land management goals related to fire and fuels management. The past several years of Forest Service R&D social science have focused on collaboration among and between communities (Brummel et al. 2010, Charney et al 2014, Cooke et al. 2016), building public trust (Steelman et al. 2015, Winter et al. 2016), delivering benefits to the American people (Hermansen-Baez et al. 2011, McCaffrey and Olsen 2012, Campbell et al, 2016), and decisionmaking practices to increase safety during wildland fires (Calkin et al. 2011a). In addition, much of this research has focused inward, within fire management organizations, to increase effectiveness and efficiency (Calkin et al. 2011a, 2015). Overall, the vision remains to work with all stakeholders to safely and effectively extinguish fire, when needed; to use fire, where allowable; to manage our natural resources; and, as a Nation, to live with wildland fire (USDA and DOI 2014).

## Public Trust and Public Perceptions

Studies to better understand what shapes public views and acceptance of different wildland fire and fuels management efforts have used a variety of methods and been applied in diverse landscapes and community types across the United States and also in Australia, Canada, and New Zealand (Chavez et al. 2008, McCaffrey 2015, McCaffrey and Olsen 2012).

This research has demonstrated that wildland fire and fuels management is a concern to individuals throughout the United States. The vast majority of populations studied (residents, landowners, and recreationists) perceive and support thinning and prescribed burning as management tools to mitigate fire risk and deliver benefits to the public through resilient landscapes (McCaffrey 2015). Forest Service R&D has found a relationship between knowledge and familiarity with a management activity and increased support for the practice. For example, knowledge about the ecological benefits of a practice is associated with increased support, particularly for more controversial aspects such as smoke from prescribed fire. Trust and confidence in the implementing agency are also key factors that influence support (Absher and Vaskey 2011, Liljeblad et al. 2010, McCaffrey and Olsen 2012, Paveglio et al. 2015). Communication, particularly when it is interactive, that provides clarification of how agency actions reduce fire risk and improve ecosystem health and that also addresses actions that seem inconsistent with shared values has been shown to be essential to maintaining trust and building support (Butry et al. 2010, Hermansen-Baez et al. 2011, McCaffrey 2015, McCaffrey and Olsen 2012, Sturtevant and Jakes 2008, Sturtevant et al. 2013).

Findings also show that most residents in the WUI recognize the risk of fire (McCaffrey and Olsen 2012); however, although it is necessary for homeowners to recognize the fire risk to become active in mitigating their fire risk, it is not a sufficient condition. Risk perception is a complex process that is shaped by individual differences in various factors, including risk tolerance and perceived values at risk. The perceived effectiveness of the risk-reduction action, confidence in one's ability to perform the action, and perceived responsibility for fire response also influence readiness to take protective actions (Chavez et al. 2008, Cooke et al. 2016, Koch et al. 2016, McCaffrey 2008, McCaffrey et al. 2011, O'Callaghan et al. 2013). Social vulnerability also has been found to potentially affect the abilities of individuals and communities to withstand adverse impacts from exposure to multiple stressors and that individuals or communities on the margins of society are generally less able to mitigate wildland fire risk or to recover from wildfires (Johnson et al. 2011; Murphy et al. 2015). It is interesting that no consistent evidence has been found to show that any specific demographic portion of the population—whether an urban or rural resident, a new or long-term homeowner, a permanent or seasonal resident, or a new or experienced forest visitor—is more or less likely to understand fire risk or to support a fuels management activity (McCaffrey 2015, McCaffrey and Olsen 2012, Tomen et al. 2014, Winter et al. 2014). Recently, USDA Forest Service R&D and partners developed a national map of WUI based on biophysical and census data designed to inform both national policy and local land management concerning the WUI. (See: https://www.nrs.fs.fed.us/data/wui; Martinuzzi et al. 2015).

## Collaboration and Planning

Collaboration can play a key role in building confidence and having stakeholders arrive at mutually acceptable wildfire risk mitigation planning (Brummel et al. 2010, Butler et al. 2015, Charnley et al. 2014, Cooke et al. 2016, Sturtevant and Jakes 2008).

Research evaluating the benefits of Community Wildfire Protection Plans (CWPPs) has shown that, although a tremendous amount of diversity exists in wildfire planning processes, this variability allows for more effective consideration of local ecological and social context (Brummel et al. 2010, Jakes et al. 2011). Defined in the 2003 Healthy Forests Restoration Act, a CWPP is a tool for bringing local, community-level solutions to wildland fire management (see https://www.forestsandrangelands.gov/communities for more information); in some cases, the efforts build on existing support for fire planning and, in others, the CWPP process itself builds support for fire planning (Jakes et al. 2011). This research has helped identify three best management practices (BMPs): (1) pay attention to problem framing, (2) choose a spatial scale in which participants can make things happen, and (3) take steps to facilitate implementation and ensure long-term success. These BMPs were found to hold true despite considerable diversity across cases (Williams et al. 2012).

Effectively mitigating wildfire risk across landscapes and regions is contingent on evaluation of both biophysical factors that influence risk transmission (e.g., wildfire spread) and social factors that influence landowners' and communities' mitigation efforts and potential losses and benefits from wildland fire. Biophysical and social processes, however, often are disconnected in mitigation planning because they work at different temporal and spatial scales. Research by Forest Service R&D has begun to show how biophysical and social data may be combined to develop wildfire risk mitigation strategies that leverage comparative advantages on the landscape, highlighting where to invest in risk mitigation and where to target education and incentive efforts toward persuading particular landowners toward greater risk mitigation efforts (Ager et al. 2015, Calkin et al. 2011a, Thompson et al. 2015, Thompson et al. 2016). Areas where coincidence of high wildfire risk transmission with low mitigation potential by landowners represent landscapes and communities where lawmakers, policymakers, and wildland fire managers might consider targeting policy interventions, such as education and technical assistance, to support greater mitigation effort among private landowners or incentives to support wildfire risk-mitigation efforts by communities that lack capacity to mitigate wildfire risk.

## Values at Risk: Promoting Fire-Adapted Communities

The increasing number of homes and rates of development in the WUI and associated effects on lives and property from wildfire, escalating costs of wildfire suppression, and changing baseline factors that have increased undesired wildfire have led to an urgent need for communities to become "adapted" to wildland fire (Murphy et al. 2016, Stein et al. 2013). During the past decade, a number of programs and initiatives in addition to the CWPP approach have been implemented to help communities prepare for wildfires and mitigate wildfire risk. At a national level, these programs and initiatives include the multiagency FIREWISE program run by the National Fire Protection Association (http://www.firewise.org) that is focused on homeowner mitigation; Ready, Set, Go!, which is administered by the International Association of Fire Chiefs and is targeted at increasing local fire department community engagement (http://iafc.org/); the Fire Adapted Communities Learning Network supported by the Forest Service and The Nature Conservancy and administered by The Watershed Research and Training Center (http://fireadaptednetwork.org); and numerous resources and certification courses available from the U.S. Fire Administration. Each program relies on a foundation comprised largely of social science and technology supported and delivered by Forest Service R&D as described in the previous sections.

Forest Service R&D research has shown that a range of outreach programs is beneficial, because no single program will be appropriate for every context (McCaffrey et al. 2011, McCaffrey 2015); however, not all communities may have access to such programs. Work examining the spatial relationship between highly fire-prone areas that ranked high in social vulnerability variables ("hot spots") showed a relative lack of wildfire risk-mitigation programs in census block groups with hot spot classifications across the Southeastern United States and suggested that poorer communities may be at a greater disadvantage than more affluent, high-fire-risk communities in these States. (Johnson et al. 2011).

To help homeowners and communities with mitigation decisions, Forest Service scientists at the Forest Products Laboratory have created an application to aid in homebuilding and community development planning that facilitates decisions concerning building materials, structural arrangements, and landscaping that mitigate wildfire risk. This application provides a visualization of why and how local wildfire risk mitigation can be achieved, even if certain building and landscape objects are ignited due to exposure to severe wildfire, and enables examination of lower costs and better aesthetics at the individual home and at the community level (Dietenberger 2010).

Results from this research by Forest Service R&D scientists and partners are being used by land and fire managers to develop projects and programs that can more effectively take into account public views and encourage proactive public participation in wildland fire and fuels management efforts. The research is also being used to help homeowners determine how best to mitigate their fire risk.

## Human Dimensions of Firefighting Organizations and Decisionmaking

Fire organizations and firefighters are faced with balancing the short-term protection of human property, infrastructure, and other values exposed to wildfire risk against the potential long-term benefits that wildfires can provide to natural systems and wildlife populations. The compressed decision timeframes imposed on fire managers during an incident are often insufficient to fully assess a range of fire management options and their respective implications for public and fire-responder safety, attainment of land and resource objectives, and future trajectories of hazard and risk. The task involves defining the landscape as a combination of biophysical and human characteristics that, when combined with fire behavior models, can give an overall picture of potential burned area for both incident-specific situational awareness and longer term risk-management planning that includes both the costs and gains of wildland fire. This work includes the Wildland Fire Decision Support System (Calkin et al. 2011b; described previously) and other operational risk applications (O'Connor et al. 2016), as well as studies focused on (1) emergency management strategies (McCaffrey et al. 2015); (2) exposure to aviation risk (Stonesifer et al. 2014); (3) effects of organizational, environmental, group, and individual characteristics on safety climate (Black and McBride 2013); and (4) evaluations of trends in social media reports (Sachdeva et al. 2016).

# Strengthened Wildland Fire Ecology Practices Supporting Landscape Restoration

**Diverse and comprehensive information and tools that characterize the ecologic costs and benefits are available to support the restoration of resilient landscapes; deliver clean, abundant water; and strengthen communities. Accessible science and technology exist for adaptive and collaborative fire management in the face of changing baseline conditions.**

## OUTCOME 5

Fire regimes are usually expressed as wildfire frequency, extent, pattern, and severity (Agee 1993, Bowman et al. 2009, Brown and Smith 2000, Keeley et al. 2009, Morgan et al. 2001). Note that in the context of fire ecology, fire severity refers to the effects of wildland fires on landscape and ecosystem components, including the human dimensions (Hardy 2005). Altered fire regimes, resulting from removal of burning by indigenous people, the effects of past land use and management activities, introduction of nonnative species, changing climate conditions, and socioeconomic influences have impacted landscape resilience and sustainable benefits for the public (Keane and Karau 2010). Forest Service R&D, along with partners, manages active research programs across the United States that have quantified the interaction of wildland fire with landscape composition, structure, and function and characterized the effects of wildland fire on ecosystem processes at multiple temporal and spatial scales. Much of this research incorporates human dimensions into studies of integrated socioecological systems (e.g., Ager et al. 2015, Fischer et al. 2016).

The products of the R&D Wildland Fire and Fuels program have contributed to understanding, predicting, assessing, and monitoring the interactions among wildland fire regimes, other ecosystem disturbances, changes in land use, climate variability and change, soil, water, vegetation, insects, disease, terrestrial and aquatic wildlife species and habitat, invasive species, and air quality. It is important to note that this body of research focuses on the potential for both negative and positive wildland fire effects on landscapes and communities (Keane and Karau 2010). Enhanced understanding of wildland fire ecology forms a sound foundation for managing wildland fire, developing and evaluating management programs, modeling outcomes, and assessing the risks and benefits of alternative management strategies focused on restoring and maintaining resilient landscapes. Over the years, much of this research has become implicit to wildland fire management (e.g., Keane and Karau 2010, Hessburg et al. 2016, Reynolds et al. 2013). The following sections briefly synthesize the tremendous amount of user-inspired wildland fire ecology produced and delivered by Forest Service R&D.

## Fire History and Changing Fire Regimes

Across the United States, land managers are dedicated to restoring and maintaining landscapes that are sustainable under changing baseline conditions, mitigating wildfire risk, conserving open space, and delivering benefits to the public from its national forests and grasslands (USDA Forest Service 2015a). Success depends on integrating science that characterizes wildland fire regimes and (1) how they have been altered with the expansion of land use during the past two centuries and (2) how they are likely to change in the future. Forest Service R&D has produced and delivered extensive knowledge, data, and applications that incorporate information about how fire regimes affect landscape composition, structure, and function across the United States. Notable examples from more than 400 studies into fire regimes and land management include Arno et al. (2008), Crawford et al. (2015), Dey et al. (2010), Hessburg et al. (2016); Heyerdahl et al. (2011), Iniguez et al. (2008), Jolly et al. (2015), Kitchen (2015), Littell et al. (2016), Miller et al. (2012), O'Connor et al. (2014), Reynolds et al. (2013), Ryan et al. (2010), Skinner et al. (2009).

Knowledge about historical fire regimes is built from proxies of fire, such as dates of scars formed on trees after fire-caused injuries, dates of post-fire vegetation, and sampling sediments in lakes for ash and charred particles. In many areas, historical records in the form of narratives and maps of historical fires (fire atlases) exist and may be used to characterize past fire regimes. The resulting site- and landscape-specific fire histories are then used to develop vegetation management approaches focused on restoring resilient landscapes and models of fire and climate interactions. These products are regularly used by Federal, State, tribal, and local governments; private organizations such as The Nature Conservancy; and individual landowners to guide land and fire management planning focused on resilient, productive landscapes.

This tremendous body of research indicates complex relationships between wildland fire and landscapes. In many arid landscapes of the Great Basin, Southwest, and Intermountain West, historical fire regimes with fires every 25 to 50 years have been changed profoundly by the introduction of nonnative annual grasses and increased land use (e.g., livestock grazing and oil and gas operations). Fires in these landscapes currently tend to be more frequent and severe, causing dramatic reductions in wildlife and water supply and quality (Finch et al. 2015, Kitchen 2015). In ponderosa and mixed conifer forests in the Western United States, fire exclusion from decades of effective fire suppression has resulted in a shift from relatively open stands maintained by frequent low-severity surface fires to denser, younger stands with higher potential for severe crown fires (Arno et al. 2008, Hessburg et al. 2016, Iniguez et al. 2008, Reynolds et al. 2013). In the Eastern United States, once abundant hardwood forests have become scarce because of the conversion to agriculture or the development of new forest structure resulting from fire exclusion (Dey et al. 2016). In the Lake States, Forest Service scientists have taken the novel approach of using witness trees from original public land surveys to reconstruct historical fire regimes (Thomas-Van Gundy and Nowacki 2013). A paradox exists when comparing historical fire regimes to contemporary fire regimes. Many landscapes of the United States historically experienced much larger fires than are common today. Studies that examine historical data along with contemporary stand structure, however, indicate that, although past fires were larger and sometimes more frequent, they were much less severe than contemporary fires. Most historical fires maintained forests of the United States by periodically consuming younger cohorts of vegetation that now serve as ladder fuels, increasing the risk of severe crown fire (Dey et al. 2016, Hessburg et al. 2016, Reynolds et al. 2013). In addition, wildfires today are made much more complex because of increased rates of expansion of development in the WUI and demands on natural resources (Thompson 2013).

In general, Forest Service R&D research into fire regimes across the United States and on diverse landscapes indicates that fire size and severity have been increasing during the past several decades. When used as a baseline compared with medium- to long-term monitoring data, results generally suggest that mechanical treatment alone does not suffice when objectives include restoring resilient and productive landscapes and that combinations of mechanical treatments, prescribed fires, and managed wildfire tend to result in sustainable landscapes that provide clean abundant water, strengthen communities, and provide opportunities to connect people with the outdoors (USDA Forest Service 2015).

## Biophysical Processes

Fire is an ecosystem disturbance. It both affects and is affected by the ecological, biologic, and abiotic process of a landscape. Examples include soil characteristics, watershed function, vegetation composition, structure and condition, insects and diseases, and fire-climate interactions. As fire interacts with the biophysical processes across the landscape, other ecosystem disturbances, and land use and land management activities and trends, it can result in either costs or benefits to landscapes or human communities.

### Soil

Soil heating during intense wildland fires or burning of treatment residue (e.g., slash piles) can alter the soil permanently, resulting in significant long-term biological, chemical, and physical effects. To better understand these long-term effects, scientists with Forest Service R&D and their partners studied the effects of fire on soils and improved modeling capability focused on immediate effects that fire can have on soils (Neary et al. 2005). The effects of fire on soils are related to intensity, or the energy output from the fire. High-intensity fires tend to decrease soil productivity, while low-intensity fires can increase soil productivity (Halofsky et al. 2011). Changes associated with different severities of wildland fires produce diverse responses in soil. Both immediate and long-term responses to fire occur (e.g, first-order and second-order fire effects). Immediate effects occur as a result of the release of chemicals in the ash created by combustion of biomass. The response of biological components (e.g., soil microorganisms and vegetation) to these changes is both dramatic and rapid. Another immediate effect of fire is the release of gases and other air pollutants by the combustion of biomass and soil organic matter (Busse et al. 2014, Butnor et al. 2016, Ericksen et al. 2008, Massman 2015, Massman et al, 2010, Neary et al. 2005, 2008, Yi et al. 2010).

### Watershed Function

Wildland fire can have substantial effects on watersheds and related ecological systems (e.g., freshwater ecosystems and water quality and supply). Any need to mitigate undesired wildland fire effects depends on the extent, continuity, and severity of the fire on the lithology, landform, and local climate. Wildland fires can have considerable effects on ecological processes, water quality and supply, species and habitats of concern, and potential for property and infrastructure damage from increased erosion and landslides and also the effectiveness of rehabilitation methods. Understanding this context is key to the effective prioritization of limited resources when conducting post-fire rehabilitation and restoration (Robichaud et al. 2016). Common practices for stabilization include seeding burned areas with either native or nonnative forbs or grasses, covering the burned surface with straw mulch or artificial materials, contour felling of logs, and covering the burned surface with wood sheds and strands (Robichaud et al. 2010).

Hydrological consequences of wildland fires depend on the intensity and the length of time the surface is exposed to smoldering and can last for decades (Woodsmith et al. 2007). Post-fire peak runoff and erosion can be orders of magnitude larger than prefire values, owing to the loss of surface cover and fire-induced changes in soil properties (Moody et al. 2013). Direct and indirect fire effects impact watershed function as large numbers of communities are surrounded by areas increasingly at risk of wildfire (Martinuzzi et al. 2015, Miller et al. 2011). The level of influence of wildfires on water quality can be substantial, depending on the severity of the wildfire, the nature of vegetation cover, and the physical and chemical characteristics of the burned area. Large and fast streamflows from burned areas can pick up and transport large amounts of debris, sediment, and chemicals that significantly affect the quality and use of water downstream. Also, wildland fires can interrupt or terminate nutrient uptake and can increase mineralization and mineral weathering (Aragai and Neary 2015).

This body of work by Forest Service R&D has contributed to a fundamental change in the understanding of fire effects on hillslope, watershed, and aquatic ecosystem processes and their recovery and has transformed emergency stabilization, rehabilitation, and restoration approaches. Proactive efforts to restore aquatic ecological processes (e.g., habitat connectivity) and ensure clean and abundant water—before the inevitable wildfires occur—are now receiving significant attention throughout the West.

## Fire-Vegetation Interactions

Effects of wildland fire on vegetation result from interactions between fire intensity and the characteristics of the plants in the burned area, both their inherent resistance to injury and their ability to recover (Brown and Smith 2000). The Forest Service R&D Wildland Fire and Fuels program's focus on fire-vegetation interactions is substantial and diverse, with more than 400 publications. For notable examples, see Dodson et al. (2008), Elliott et al. (2009), Hessburg et al. (2016), Hollingsworth et al. (2013), Hood et al. (2015), Jenkins et al. (2011), Keane and Parsons (2010), Knapp et al. (2009), Reynolds et al. (2013), Sturtevant et al. (2014).

Fuel characteristics, topography, soil components, wind speed, and the composition and structure of plant communities can cause lethal heat zones created by fire to vary significantly in time and space (Keane et al. 2013). Wildland fire causes significant, immediate changes in vegetation, eliminating some species or causing others to appear where they were not present before the fire (e.g., nonnative colonizers).

Certain vegetation species can survive based on a single attribute; others survive based on multiple adaptations (Brown and Smith 2000). Some will be present after fire only if regenerative structures survive and produce sprouts, because their seedlings are unlikely to survive in post-fire environments (Hutchinson et al. 2012). Species of plants that cannot resprout after top-killing must establish from seed (Cottrel et al. 2008); some species can successfully recover from fire both by resprouting and by seedling establishment. In large areas that experience high-severity fire consuming the organic components of the soil, reproduction occurs from seeds dispersed from vegetation adjacent to the burned area (Lorenz et al. 2008). The immediate response of plants can differ within the same fire because of variations in the pattern of burn severity (Stueve et al. 2009). Post-fire vegetation communities are usually an assemblage of many of the species that were growing on the site and represented in the seedbank at the time of the fire. Many of the seedlings present in the first few post-fire years may have grown from seeds formed or resprouting species such as chaparral and certain tree species (Bradley et al. 2016). The only locations in which new species are likely to be added to the plant community are microsites that are severely burned and receptive to germination and establishment of seeds from species dispersed from off of the site (Cottrel et al. 2008, Lorenz et al. 2008). During the past several years, the Joint Fire Science Program has had an active line of work investigating fire effects on vegetation (see http://www.firescience.gov for more information).

## Insects and Disease

Insect disturbance is thought to increase wildfire risk by increasing dead fuels across large landscapes; however, insect disturbances also modify tree species composition and structure to influence fire disturbances over longer time scales. Forest Service R&D scientists and their partners have investigated the short- and long-term interactions of both the effects of wildfire-stressed forests on insect population and insect damage on subsequent wildfires. For examples across the United States, see James et al. (2011), Metz et al. (2013), Negron et al. (2008), Preisler et al. (2010), and Trotter (2013).

Single-age stand conditions and warm climate patterns have led to a large-scale outbreak of mountain pine beetle (*Dendroctonus ponderosae*) throughout the Rocky Mountain West. Once infested, trees die, and their needles turn red. Scientists have debated the effect these beetle-killed trees might have on fire behavior, but little is yet known. For example, beetle-killed trees lose their needles over time, and once all the needles have dropped, crown fire danger largely disappears; however, researchers currently do not know how long that process takes after infestation and, therefore, how long forests remain at risk for crown fire initiation and spread (the same may be said about drought mortality and wildfire; see the following section on climate change). Moreover, these red-needled trees have lower foliar moisture contents than do unattacked trees, leading to increased crown fire potential. Forest Service R&D, along with managers and partners, has focused on the time it takes for trees to lose their needles and found that after a beetle attack some needles stay on trees for up to 4 years (Collins et al. 2012, Jolly et al. 2012b). Researchers also investigated the moisture content of beetle-killed foliage before needle loss. They found that red needles have 10 times less moisture than healthy foliage and that red needles ignite 4 times faster than green needles. As a consequence, forests with a large number of beetle-killed trees are at a significantly higher risk of surface fires igniting the crown. Such low fuel moistures could also result in beetle-killed trees spotting ahead of the fire (Jolly et al. 2012a). Hood et al. (2015) found that treatment with low-severity fire (either prescribed fire or managed wildfire) increased tree defenses against insect infestations.

## Climate Change

A warming climate is predicted to alter fire regimes across the United States (Keane and Lohman 2010, Keane et al. 2013, Littell et al. 2016, Sommers et al. 2014), which is likely to have significant effects on many ecosystems. Predicting future fire occurrence and severity is challenging because of the uncertainty in future climate, associated vegetation changes, fuel distribution, and land use patterns across the landscape. Accurate predictions are needed, however, to improve understanding of how climate variability will affect disturbance regimes, carbon dynamics, and air quality and, ultimately, to inform fire and land management focused on establishing and maintaining resilient and sustainable landscapes and delivering benefits to the public (USDA Forest Service 2015). Empirical and modeling studies have been implemented by Forest

Service R&D and partners across diverse landscapes and at a variety of spatial and temporal scales to characterize climate-fire relationships. At the finest spatial and temporal scales, empirical data and modeling have been used to quantify the effects of local climatology on fire behavior and emissions. The regional fire history datasets have been compiled over large regions to determine fine- to broad-scale fire-climate patterns over long time periods (Heyerdahl et al. 2008, 2011; Jolly et al. 2015; Kitchen 2015; Morgan et al. 2014; Trouet et al. 2010). Modeling studies have been used to extend and generalize the empirical climate-fire information from fire history databases across the United States (Hemstrom et al. 2014, Keane and Lohman 2010, Keane et al. 2013, Lohman et al. 2011, Pollina et al. 2013, Sample et al. 2014). Results generally indicate that a large amount of variability is in future landscapes because of climate change and fire interactions.

Although large wildfires are less common in the Northeastern United States than in other parts of the country, the socioecological impacts of these events can be substantial. A combination of densely populated locales and the inherent challenge of accurately forecasting rare events accentuates the difficulties that land and fire managers face when managing large wildfires in the Northeast. Forest Service R&D scientists, along with partners, developed a wildfire weather climatology application that enables wildland managers to know where and when large wildfires have occurred in the past so future wildfire events can be predicted and managed with greater accuracy and confidence.

In much the same way that BehavePlus (Andrews 2014) integrates mathematical models of fire behavior, the First Order Fire Effects Model (FOFEM; Reinhardt and Keane 1998) integrates numerous models that predict vegetation mortality, fuel consumption, and soil heating. CONSUME (Ottmar et al. 1993) is another similar integration of mathematical models that predicts fuel consumption, heat release, and emissions from wildland fires.

## Conclusion

Since the mid-20th century, the corpus of wildland fire science generally has concentrated on helping practitioners and leadership determine which fires are "good" fires and which fires are "bad" fires. Much of this body of knowledge was developed by Forest Service fire scientists. To provide an implementation framework for this notion of good fire and bad fire, the historian Stephen Pyne describes three general strategies for wildland fire management and response: (1) regressive, (2) proactive, and (3) reactive (Pyne 2013). A template of scientifically defined costs and benefits of fires is implicit in each strategy.

The regressive strategy is defined by Pyne as the attempt to extinguish every fire quickly and aggressively, using every firefighting asset available (Pyne 2013). This strategy follows the historical paramilitary narrative of wildfire as a preventable natural disaster that needs to be attacked for the sake of public safety and saving lives, property, infrastructure, and natural resources. A need certainly exists for aggressive suppression in certain circumstances, and this strategy has been well grounded in the public's understanding of fire through successful public service campaigns such as the Smokey Bear campaign.

Pyne's second strategy—proactive—characterizes fire in terms of its environment. This strategy involves actively changing landscapes' fire environments to result in fire behavior that is desired and relatively easily suppressed when it is not desired (Pyne 2013). The proactive strategy identifies the WUI as a critical zone to be prioritized when allocating management resources and firefighting assets. This strategy involves collaboration across jurisdictions at landscape scales where communities work with State, local, and tribal organizations to adapt fire-ready strategies that make them resilient to the eventual wildfire. Further, the proactive strategy sets objectives for landscapes that produce goods and services for the public (Pyne 2013).

The third strategy described by Pyne—the reactive strategy—focuses on holistically characterizing diverse landscapes (or firescapes) in terms of their fire environment, including land use change, changing baseline conditions, and other sources of disturbance, such as invasive species, insects, and disease. This strategy considers wildfires as inevitable, addresses every fire with the same approach regardless of source, and mandates managing wildfires as a cost-effective way to manage productive landscapes and mitigate the risk of future undesired wildfires (Pyne 2013). The reactive strategy fully embraces "appropriate management response" as articulated in current Federal wildland fire policy and considers wildfires as an effective management alternative to accomplish fuel reduction similar to mechanical treatments and prescribed fires. Perhaps most importantly, this strategy emphasizes integrated, science-based risk assessments and response protocols that maximize firefighter and public safety. Under extreme conditions, there is no reason for crews to try to do what cannot be done (Pyne 2013). It follows the same model as hurricanes, so that evacuation and post-fire response and recovery are the main tactics, as opposed to aggressive attack. This third strategy challenges scientists, managers, and decisionmakers to formalize and be accountable for the narrative that science informs and that management adapts.

In reality, all three strategies are applied today. Aggressive suppression is often the expedient strategy, which often results in pushing wildfire risk that may have been mitigated by less aggressive suppression into a challenge for future managers (Pyne 2013). Often, sociopolitical pressures are at play during critical decisions about suppression tactics and can outweigh approaches based on science. Wildland fire science can play a role in blending these three strategies into an advantageous approach to wildland fire management and response by helping to define good and bad fire in a way that is accessible to practitioners and well understood by the public. A more formal approach is needed so that science becomes implicit in decisionmaking and policymaking. Six critical elements are necessary for this to occur.

1. Formal mechanisms that deliver science at all levels and themes of decisionmaking and leadership that fosters cooperation in determining the requirements for new short- and long-term science.
2. A solid foundation in comprehensive, consistent, and repeatable wildland fire risk assessment that will inform practitioners and the public of the costs and benefits of wildland fire.
3. Science and technology that reduces uncertainty around decisions about less aggressive suppression tactics.
4. Further integration and investment that promote public education and enhanced practitioner training.
5. Building strategic science positions into the scalable Incident Command System used for wildfire response to effectively deliver science during times of critical decisionmaking.
6. Accessible information for building programs focused on large, collaborative landscape management activities that both reduce the risk of undesired fire and take advantage of the benefits of desired fire.

Outcomes from wildland fire science research, the existing culture of science/management networks, and wildland fire strategic development have made great progress in addressing each of these elements; however, much work needs to be accomplished. New mechanisms like the Federal Fire Science Coordination Council and the Joint Fire Science Program's Fire Science Exchange Networks have great potential to address these elements into the future. Realizing a true science-informed national wildland fire management and response capacity requires advocacy at the highest levels of governance and investment in national programs that focus on—

- Establishing formal mechanisms for knowledge exchange and determining goals for strategic science.
- Enhancing and maintaining data and systems for risk assessment and mitigation that enable cost/benefit analysis in both tactical and strategic decisionmaking.
- Providing public education about good and bad fire and enhanced, science-based practitioner training.

With a focus on enhancing and formalizing the scientific foundations of wildland fire management and response, the Forest Service R&D Wildland Fire and Fuels program will continue to play a critical role in these areas and be the global leader in providing visionary and accessible wildland fire science for the future.

# Literature Cited

Abrams, J.; Nielsen-Pincus, M.; Paveglio, T; Moseley, C. 2016. Community wildfire protection planning in the American West: homogeneity within diversity? Journal of Environmental Planning and Management. 59(3): 557–572.

Absher, J.D.; Vaske, J.J. 2011. The role of trust in residents' fire wise actions. International Journal of Wildland Fire. 20: 318–325.

Achtemeier, G.L; Goodrick, S.L; Liu, Y; Garcia-Menendez, F.; Hu, Y; Odman, M. 2011. Modeling smoke plume-rise and dispersion from Southern United States prescribed burns with daysmoke. Atmosphere. 2(3): 358–388.

Adetona, O; Dunn, K.; Hall, D.B.; Achtemeier, G.; Stock, A.; Naeher, L.P. 2011. Personal $PM_{(2.5)}$ exposure among wildland firefighters working at prescribed forest burns in Southeastern United States. Journal of Occupational and Environmental Hygiene. 8(8): 503–511.

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press. 493 p.

Ager, A.A.; Day, M.A.; Short, K.C.; Evers, C.R. 2016. Assessing the impacts of federal forest planning on wildfire risk-mitigation in the Pacific Northwest, USA. Landscape and Urban Planning. 147: 1–17.

Ager, A.A; Kline, J.D.; Fischer, A.P. 2015. Coupling the biophysical and social dimensions of wildfire risk to improve wildfire mitigation planning. Risk Analysis. 35(8): 1393–1406.

Ager, A.A.; Vaillant, N.M.; Finney, M.A. 2011. Integrating fire behavior models and geospatial analysis for wildland fire risk assessment and fuel management planning. Journal of Combustion. 19 p. doi:http://dx.doi.org/10.1155/2011/572452.

Ager, A.A.; Vaillant, N.M.; Owens; D.E.; Brittain, S.; Hamann, J. 2012. Overview and example application of the Landscape Treatment Designer. Gen. Tech. Rep. PNW-GTR-859. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 11 p.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-GTR-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Andrews, P.L. 2014. Current status and future needs of the BehavePlus Fire Modeling System. International Journal of Wildland Fire. 23: 21–33.

Aregai, T.; Neary, D. 2015. Water quality impacts of forest fires. Pollution Effects and Control. 3(2): 1–7.

Arno, S.F.; Östlund, L.; Keane, R.E. 2008. Living artifacts: the ancient ponderosa pines of the West. Montana: The Magazine of Western History. Spring 2008: 55–67.

Association for Fire Ecology [AFE] and The Nature Conservancy [TNC]. 2015. Reduce wildfire risks or we'll continue to pay more for fire disasters. Eugene, OR: Association for Fire Ecology. 13 p. http://fireecology.org/Resources/Documents/Reduce-WIldfire-Risk-16-April-2015-Final-Print.pdf. (1 October 2016).

Black, A.E.; McBride, B.B. 2013. Safety climate in the US federal wildland fire management community: influences of organizational, environmental, group, and individual characteristics. International Journal of Wildland Fire. 22(6): 850–861.

Bowman, D.M.; Balch, J.K.; Artaxo, P.; Bond, W.J.; Cochrane, M.A.; D'Antonio, C.M.; DeFries, R.S.; Doyle, J.C.; Harrison, S.P.; Johnston, F.H.; Keeley, J.E.; Krawchuk, M.A.; Kull, C.A.; Marston, J.B.; Moritz, M.A.; Prentice, I.C.; Roos; Scott, A.C.; Swetnam, T.W.; van der Werf, G.R.; Pyne, S.J. 2009. Fire in the Earth system. Science. 324(5926): 481–484. http://www.sciencemag.org/cgi/content/full/324/5926/481. (1 October 2016).

Bradley, J.C.; Will, R.E.; Stewart, J.F.; Nelson, C.D.; Guldin, J.M. 2016. Post-fire resprouting of shortleaf pine is facilitated by a morphological trait but fire eliminates shortleaf x loblolly pine hybrid seedlings. Forest Ecology and Management. 379: 146–152.

Brown, J.K.; Smith, J.K. 2000. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 257 p. Vol. 2.

Brummel, R.F.; Nelson, K.C.; Grayzeck, S.; Jakes, P.J.; Williams, D.R. 2010. Social learning in a policy-mandated collaboration: community wildfire protection planning in the Eastern United States. Journal of Environmental Planning and Management. 53(6): 681–699.

Busse, M.D.; Hubbert, K.R.; Moghaddas, E.E.Y. 2014. Fuel reduction practices and their effects on soil quality. Gen. Tech. Rep. PSW-GTR-241. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 156 p.

Butler, B.; Forthofer, J. 2010. Firefighter safety zone: the effect of terrain slope of separation distance. In: Viegas, D. X., ed. Proceedings, 6th international conference on forest fire research; 15–18 November; Coimbra, Portugal: University of Coimbra. 3 p.

Butler, B.W. 2010. Characterization of convective heating in full scale wildland fires. In: Viegas, D.X., ed. Proceedings, 6th international conference on forest fire research; 15–18 November; Coimbra, Portugal: University of Coimbra. 9 p.

Butler, B.W.; Webb, J.; Hogge, J.; Wallace, T. 2015. Vegetation clearance distances to prevent wildland fire caused damage to telecommunication and power transmission infrastructure. In: Keane, R.E.; Jolly, M.; Parsons, R.; Riley, K, eds. Proceedings, large wildland fires conference; 19–23 May, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 35–40.

Butler, W.H.; Monroe, A.; McCaffrey, S. 2015. Collaborative implementation for ecological restoration on U.S. public lands: implications for legal context, accountability, and adaptive management. Environmental Management. 55(3): 564–577.

Butnor, J.R.; Johnsen, K.H.; Nelson, C.D. 2016. Changes in soil chemistry six months after prescribed fire in a longleaf pine plantation in Mississippi. In: Proceedings, 18th biennial southern silvicultural research conference. e-Gen. Tech. Rep. SRS-212. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 2 p.

Butry, D.T.; Prestemon, J.P.; Abt, K.L. 2010. Optimal timing of wildfire prevention education. Ecology and the Environment. 137: 197–206.

Calkin, D.C.; Finney, M.A.; Ager, A.A.; Thompson, M.P.; Gebert, K.M. 2011a. Progress towards and barriers to implementation of a risk framework for US federal wildland fire policy and decision making. Forest Policy and Economics. 13(5): 378–389.

Calkin, D.E.; Thompson, M.P.; Finney, M.A. 2015. Negative consequences of positive feedbacks in US wildfire management. Forest Ecosystems. 2: 9.

Calkin, D.E.; Thompson, M.P.; Finney, M.A.; Hyde, Kevin D. 2011b. A real-time risk assessment tool supporting wildland fire decisionmaking. Journal of Forestry. 109(5): 274–280.

Campbell, R.M.; Venn, T.J.; Anderson, N.M. 2016. Social preferences toward energy generation with woody biomass from public forests in Montana, USA. Forest Policy and Economics. 73: 58–67.

Cannon, J.B.; O'Brien, J.J.; Loudermilk, E.L.; Dickinson, M.B.; Peterson, C.J. 2014. The influence of experimental wind disturbance on forest fuels and fire characteristics. Forest Ecology and Management. 330: 294–303.

Champ, P.A.; Donovan, G.H.; Barth, C.M. 2013. Living in a tinderbox: wildfire risk perceptions and mitigating behaviours. International Journal of Wildland Fire. 22: 832–840.

Charnley, S.; Long, J.W.; Lake, F.K. 2014. Collaboration in national forest management. In: Long, J.W.; Quinn-Davidson, L.; Skinner, C.N., eds. Science synthesis to support socioecological resilience in the Sierra Nevada and southern Cascade Range. Gen. Tech. Rep. PSW-GTR-247. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 663–704 p.

Charnley, S.; Poe, M.R.; Ager, A.A.; Spies, T.A.; Platt, E.K.; Olsen, K.A. 2015. A burning problem: social dynamics of disaster risk reduction through wildfire mitigation. Human Organization. 74(4): 329–340.

Chatziefstratiou, E.K.; Bohrer, G.; Bova, A.S.; Subramanian, R.; Frasson, R.P.M.; Scherzer, A.; Butler, B.W.; Dickinson, M.B. 2013. FireStem2D—a two-dimensional heat transfer model for simulating tree stem injury in fires. PLOS ONE. 8(7): e70110.

Chavez, D.J.; Absher, J.D.; Winter, P.L. 2008. Fire social science research from the Pacific Southwest research station: studies supported by national fire plan funds. Gen. Tech. Rep. PSW GTR-209. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 251 p.

Cochrane, M.A.; Moran, C.J.; Wimberly, M.C.; Baer, A.D.; Finney, M.A.; Beckendorf, K.L.; Eidenshink, J.; Zhu, Z. 2012. Estimation of wildfire size and risk changes due to fuels treatments. International Journal of Wildland Fire. 21: 357–367.

Cohen, J.D. 2000. Preventing disaster: home ignitability in the wildland urban interface. Journal of Forestry. 98(3): 15–21.

Cohen, J.D.; Finney, M.A. 2010. An examination of fuel particle heating during fire spread. In: Viegas, D.X., ed. Proceedings, 6th international conference on forest fire research; 15–18 November; Coimbra, Portugal: University of Coimbra. 13 p.

Collins, B.J.; Rhoades, C.C.; Battaglia, M.A.; Hubbard, R.M. 2012. Effects of salvage logging on fire risks after bark beetle outbreaks in Colorado lodgepole pine forests. Fire Management Today. 72(3): 18–22.

Conard, S.G.; Solomon, A.M. 2009. Effects of wildland fire on regional and global carbon stocks in a changing environment. In: Bytnerowicz, A.; Arbaugh, M; Andersen, C.; Riebau, A., eds. Wildland fires and air pollution: developments in environmental science 8. Amsterdam: Elsevier. 109–138 p.

Cooke, B.; Williams, D.; Paveglio, T.; Carroll, M. 2016. Living with fire: how social scientists are helping wildland-urban interface communities reduce wildfire risk. Science You Can Use Bulletin, Issue 19. Fort Collins, CO: Rocky Mountain Research Station. 9 p.

Contreras, M.A.; Parsons, R.A.; Chung, W. 2012. Modeling tree-level fuel connectivity to evaluate the effectiveness of thinning treatments for reducing crown fire potential. Forest Ecology and Management. 264: 134–149.

Cottrell, T.R.; Hessburg, P.F.; Betz, J.A. 2008. Seed invasion filters and forest fire severity. Fire Ecology. 4(1): 87–100.

Crawford, J.N.; Mensing, S.A.; Lake, F.K.; Zimmerman, S.R. 2015. Late Holocene fire and vegetation reconstruction from the western Klamath Mountains, California, USA: a multi-disciplinary approach for examining potential human land-use impacts. The Holocene. 25(8): 1341–1357.

Crookston, N.L.; Dixon, G.E. 2005. The Forest Vegetation Simulator: a review of its structure, content, and applications. Computers and Electronics in Agriculture. 49(1): 60–80.

Crookston, N.L.; Rehfeldt, G.E.; Dixon, G.E.; Weiskittel, A.R. 2010. Addressing climate change in the Forest Vegetation Simulator to assess impacts on landscape forest dynamics. In: Jain, T.B.; Graham, R.T.; Sandquist, J., eds. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate. Proceedings, 2009 national silviculture workshop. 15–18 June; Boise, ID. Proceedings RMRS-P-61. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 273.

Cunningham, P.; Goodrick, S.L. 2013. High-resolution numerical models for smoke transport in plumes from wildland fires. In: Qu, J.J.; Sommers, W.T.; Yang, R.; Riebau, A.R., eds. Remote sensing and modeling applications to wildland fires. Beijing: Tsinghua University Press; New York: Springer. 67–79 p.

Dey, D.C.; Royo, A.A.; Brose, P.H.; Hutchinson, T.F.; Spetich, M.A.; Stoleson, S.H. 2010. An ecologically based approach to oak silviculture: a synthesis of 50 years of oak ecosystem research in North America. Revista Columbia Forestal. 13(2): 201–222.

Dey, D.C.; Schweitzer, C.J.; Kabrick, J.M. 2016. Silviculture to restore oak woodlands. In: Proceedings, 18th biennial southern silvicultural research conference. e-Gen. Tech. Rep. SRS-212. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 10 p.

Dietenberger, M.A. 2010. Ignition and flame-growth modeling on realistic building and landscape objects in changing environments. International Journal of Wildland Fire. 19(2): 228–237.

Dillon, G.K.; Menakis, J.; Fay, F. 2015. Wildland fire potential: a tool for assessing wildfire risk and fuels management needs. In: Keane, R.E.; M. Jolly; R. Parsons; K. Riley. Proceedings, large wildland fires conference; 19–23 May, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 60–76 p.

Dodson, E.K.; Peterson, D.W.; Harrod, R.J. 2008. Understory vegetation response to thinning and burning restoration treatments in dry conifer forests of the eastern Cascades, USA. Forest Ecology and Management. 255: 3130–3140.

Elliott, K.J.; Vose, J.M.; Hendrick, R.L. 2009. Long-term effects of high intensity prescribed fire on vegetation dynamics in the Wine Spring Creek Watershed, Western North Carolina, USA. Fire Ecology. 5(2): 66–85.

Erickson, H.E.; White, R. 2008. Soils under fire: soils research and the Joint Fire Science Program. Gen. Tech. Rep. PNW-GTR-759. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.

Evangeliou, N.; Balkanski, Y.; Hao, W.M.; Petkov, A.; Silverstein, R.P.; Corley, R.; Nordgren, B.L.; Urbanski, S.P.; Eckhardt, S.; Stohl, A.; Tunved, P.; Crepinsek, S.; Jefferson, A.; Sharma, S.; Nojgaard, J.K.; Skov, H. 2016. Wildfires in northern Eurasia affect the budget of black carbon in the Arctic—a 12-year retrospective synopsis (2002–2013). Atmospheric Chemistry and Physics. 16: 7587–7604.

Ex, S.; Smith, F.W.; Keyser, T.L. 2015. Characterizing crown fuel distribution for conifers in the interior Western United States. Canadian Journal of Forest Research. 45(7): 950–957.

Finch, D.; Boyce, D.; Chambers, J.; Colt, C.; McCarthy, C.; Kitchen, S.; Richardson, B.; Rowland, M.; Rumble, M.; Schwartz, M.; Tomosy, M.; Wisdom, M. 2015. USDA Forest Service sage-grouse conservation science strategy. Washington, DC: U.S. Department of Agriculture, Forest Service. 39 p.

Finney, M.A. 2004. FARSITE: Fire Area Simulator-model development and evaluation. Res. Pap. RMRS-RP-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Finney, M.A. 2006. An overview of flammap fire modeling capabilities. In: Andrews, P.L.; Butler, B.W., eds. Fuels management—how to measure success: conference proceedings. 28–30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 213–220 p.

Finney, M.A.; Cohen, J.D.; Forthofer; J.M.; McAllister, S.S.; Gollner, M.J.; Gorham, D.J.; Saito, K.; Akafuah, N.K.; Adam, B.A.; English, J.D. 2015. Role of buoyant flame dynamics in wildfire spread. PNAS. doi:10.1073/pnas.1504498112.

Finney, M.A.; Cohen, J.D.; McAllister, S.S.; Jolly, W.M. 2012. On the need for a theory of wildland fire spread. International Journal of Wildland Fire. 22: 25–36.

Fischer, A P.; Spies, T.A; Steelman, T.A; Moseley, C.; Johnson, B.R; Bailey, J.D; Ager, A.A; Bourgeron, P.; Charnley, S.; Collins, B.M; Kline, J.D; Leahy, J.E; Littell, J.S; Millington, J.; Nielsen-Pincus, M.; Olsen, C.S; Paveglio, T.B; Roos, C.I.; Steen-Adams, M.M; Stevens, F.R; Vukomanovic, J.; White, E.M; Bowman, D. 2016. Wildfire risk as a socioecological pathology. Frontiers in Ecology and the Environment. 14(5): 276–284.

Frankman, D.; Webb, B.W.; Butler, B.W.; Jimenez, D.; Forthofer, J.M.; Sopko, P.; Shannon, K.S.; Hiers, J. Kevin; Ottmar, R.D. 2012. Measurements of convective and radiative heating in wildland fires. International Journal of Wildland Fire. 22: 157–167.

Freeborn, P.H.; Cochrane, M.A.; Jolly, W.M. 2015. Relationships between fire danger and the daily number and daily growth of active incidents burning in the northern Rocky Mountains, USA. International Journal of Wildland Fire. doi:http://dx.doi.org/10.1071/WF14152. (3 March 2017).

Gibson, K.; Negron, J.F. 2009. Fire and bark beetle interactions. In: Hayes, J.L.; Lundquist, J.E., eds. The Western Bark Beetle Research Group: a unique collaboration with Forest Health Protection: proceedings of a symposium at the 2007 Society of American Foresters conference. Gen. Tech. Rep. PNW-GTR-784. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 51–70.

Goodrick, S.L.; Achtemeier, G.L.; Larkin, N.K.; Liu, Y.; Strand, T.M. 2012. Modelling smoke transport from wildland fires: a review. International Journal of Wildland Fire. 22(1): 83–94. http://dx.doi.org/10.1071/WF11116. (3 March 2017).

Guyette, R.P.; Stambaugh, M.C.; Dey, D.C.; Muzika, R. 2012. Predicting fire frequency with chemistry and climate. Ecosystems. 15: 322–335.

Halofsky, J.E.; Donato, D.C.; Hibbs, D.E.; Campbell, J.L.; Donaghy Cannon, M.; Fontaine, J.B.; Thompson, J.R.; Anthony, R.G.; Bormann, B.T.; Kayes, L.J.; Law, B.E.; Peterson, D.L.; Spies, T.A. 2011. Mixed-severity fire regimes: lessons and hypotheses from the Klamath-Siskiyou ecoregion. Ecosphere. 2(4): 1–9. doi:10.1890/ES10-00184.1.

Hao, W.M.; Larkin, N.K. 2014. Wildland fire emissions, carbon, and climate: wildland fire detection and burned area in the United States. Forest Ecology and Management. 317: 20–25.

Hardy, C.C. 2005. Wildland fire hazard and risk: problems, definitions, and context. Forest Ecology and Management. 211: 73–82.

Hardy, C.C.; Heilman, W.; Weise, D.; Goodrick, S.; Ottmar, R. 2008. Fire behavior science advancement plan: a plan for addressing physical fire processes within the core fire sciences portfolio. Final report to the Joint Fire Science Program Governing Board. https://www.firescience.gov/projects/08-S-01/project/08-S-01_final_report_08-s-01.pdf. (1 October 2016).

Harrington, M. 2008. What kind of cutting and thinning can prevent crown fires? In: Ritter, S., ed. EcoReport. Missoula, MT: U.S. Department of Agriculture, Forest Service, Bitterroot Ecosystem Management Research Project: 7–12.

Hasburgh, L.E.; White, R.H.; Dietenberger, M.A.; Boardman, C.R. 2015. Comparison of the heat release rate from the mass loss calorimeter to the cone calorimeter for wood-based materials. In: Proceedings, fire and materials 14th international conference and exhibition; 2–4 February; San Francisco, CA. 116–126.

Heilman, W.E.; Clements, C.B.; Seto, D.; Bian, X.; Clark, K.L.; Skowronski, N.S.; Hom, J.L. 2015. Observations of fire-induced turbulence regimes during low-intensity wildland fires in forested environments: implications for smoke dispersion. Atmospheric Science Letters. doi:10.1002/asl.581.

Heilman, W.E.; Liu, Y.; Urbanski, S.; Kovalev, V.; Mickler, R. 2014. Wildland fire emissions, carbon, and climate: plume rise, atmospheric transport, and chemistry processes. Forest Ecology and Management. 317: 70–79.

Hemstrom, M.A.; Halofsky, J.E.; Conklin, D.R.; Halofsky, J.S.; Bachelet, D.; Kerns, B.K. 2014. Developing climate-informed state-and-transition models. In: Halofsky, J.E.; Creutzburg, M.K.; Hemstrom, M.A., eds. Integrating social, economic, and ecological values across large landscapes. Gen.Tech. Rep. PNW-GTR-896. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 175–202. Chapter 7.

Hermansen-Baez, L.A.; Prestemon, J.P.; Butry, D.T.; Abt, K.L.; Sutphen, R. 2011. The economic benefits of wildfire prevention education. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 2 p.

Hessburg, P.F.; Spies, T.A.; Perry, D.A.; Skinner, C.N.; Taylor, A.H.; Brown, P.M.; Stephens, S.L.; Larson, A.J.; Churchill, D.J.; Povak, N.A.; Singleton, P.H.; McComb, B.; Zielinski, W.J.; Collins, B.M.; Salter, R.B; Keane, J.J.; Franklin, J.F.; Riegel, G. 2016. Tamm review: management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. Forest Ecology and Management. 366: 221–250.

Heyerdahl, E.K.; Brown, P.M.; Kitchen, S.G.; Weber, M.H. 2011. Multicentury fire and forest histories at 19 sites in Utah and Eastern Nevada. Gen. Tech. Rep. RMRS-GTR-261WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 192 p.

Heyerdahl, E.K.; Morgan, P.; Riser, J.P. 2008. Crossdated fire histories (1650–1900) from ponderosa pine-dominated forests of Idaho and Western Montana. Gen. Tech. Rep. RMRS-GTR-214WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 83 p.

Hoffman, C.M.; Ziegler, J.; Canfield, J.; Linn, R.R.; Mell, W.; Sieg, C.H.; Pimont, F. 2015. Evaluating crown fire rate of spread predictions from physics-based models. Fire Technology. doi:10.1007/s10694-015-0500-3.

Holden, Z.A.; Abatzoglou, J.T.; Luce, C.H.; Baggett, L.S. 2011. Empirical downscaling of daily minimum air temperature at very fine resolutions in complex terrain. Agricultural and Forest Meteorology. 151: 1066–1073.

Hollingsworth, L.T.; Kurth, L.L.; Parresol, B.R.; Ottmar, R.D.; Prichard, S.J. 2012. A comparison of geospatially modeled fire behavior and fire management utility of three data sources in the Southeastern United States. Forest Ecology and Management. 273: 43–49.

Hollingsworth, L.T.; Menakis, J. 2010. Using the Large Fire Simulator System to map wildland fire potential for the conterminous United States. In: Wade, D.D.; Robinson, M.L., eds. Proceedings, 3rd fire behavior and fuels conference; 25–29 October; Spokane, WA. Birmingham, AL: International Association of Wildland Fire. 1 p.

Hollingsworth, T.N.; Johnstone, J.F.; Bernhardt, E.L.; Chapin, F.S., III. 2013. Fire severity filters regeneration traits to shape community assembly in Alaska's Boreal Forest. PLOS ONE. 8(2): e56033. 11 p.

Hood, S.; Sala, A.; Heyerdahl, E.K.; Boutin, M. 2015. Low-severity fire increases tree defense against bark beetle attacks. Ecology. 96(7): 1846–1855.

Hudak, A.T.; Rickert, I.; Morgan, P.; Strand, E.; Lewis, S.A.; Robichaud, P.R.; Hoffman, C.; Holden, Z.A. 2011. Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central, Idaho, USA. Gen. Tech. Rep. RMRS-GTR-252. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 60 p.

Hutchinson, T.F.; Long, R.P.; Rebbeck, J; Sutherland, E.K.; Yaussy, D.A. 2012. Repeated prescribed fires alter gap-phase regeneration in mixed-oak forests. Canadian Journal of Forest Research. 42: 303–314.

Iniguez, J.M.; Swetnam, T.W.; Yool, S. 2008. Topography affected landscape fire history patterns in Southern Arizona, USA. Forest Ecology and Management. 256: 295–303.

Jakes, P.J.; Nelson, K.C.; Enzler, S.A.; Burns, S.; Cheng, A.S.; Sturtevant, V.; Williams, D.R.; Bujak, A.; Brummel, R.F.; Grayzeck-Souter, S.; Staychock, E. 2011. Community wildfire protection planning: is the Healthy Forests Restoration Act's vagueness genius? International Journal of Wildland Fire. 20: 350–363.

James, P.A.; Fortin, M.J.; Sturtevant, B.R.; Fall, A.; Kneewhaw, D. 2011. Modeling spatial interactions among fire, spruce budworm, and logging in the boreal forest. Ecosystems. 14: 60–75.

Jenkins, M.A.; Klein, R.N.; McDaniel, V.L. 2011. Yellow pine regeneration as a function of fire severity and post-burn stand structure in the southern Appalachian Mountains. Forest Ecology and Management. 262(4): 681–691.

Johnson G.C.; Poudyal, N.C.; Goodrick, S.; Bowker, J.M.; Malone, S.; Gan, J. 2011. Wildland fire risk and social vulnerability in the Southeastern United States: an exploratory spatial data analysis approach. Forest Policy and Economics. 13: 24–36.

Joint Fire Science Program [JFSP]. 2009. A powerful new planning environment for fuels managers: the interagency fuels treatment decision support system. Fire Science Digest. December(7). 12 p. http://www.firescience.gov/Digest/FSdigest7.pdf. (1 October 2016).

Jolly, W.M.; Andrews, P.L.; Bradshaw, L.S. 2005. The wildland fire assessment system (WFAS): a web-based resource for decision support. In: Proceedings, east fire conference; Fairfax, VA. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Fire Behavior Research Work Unit. 4 p. http://www.comet.ucar.edu/outreach/abstract_final/EastFIREConfProc/Abstracts/Session%203C%20PDF/3C_Jolly.pdf. (3 March 2017).

Jolly, W.M.; Cochrane, M.A.; Freeborn, P.H.; Holden, Z.A.; Brown, T.J.; Williamson, G.J.; Bowman, D.M. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. Nature Communications. 6: 7537.

Jolly, W.M.; McAllister, S.; Finney, M.A.; Hadlow, A. 2010. Time to ignition is influenced by both moisture content and soluble carbohydrates in live Douglas fir and Lodgepole pine needles. In: Viegas, D.X., ed. Proceedings, 6th international conference on forest fire research; 15–18 November; Coimbra, Portugal: University of Coimbra. 8 p.

Jolly, W.M.; Parsons, R.A.; Hadlow, A.M.; Cohn, G.M.; McAllister, S.S.; Popp, J.B.; Hubbard, R.M.; Negron, J.F. 2012b. Relationships between moisture, chemistry, and ignition of Pinus contorta needles during the early stages of mountain pine beetle attack. Forest Ecology and Management. 269: 52–59.

Jolly, W.M.; Parsons, R.; Varner, J.M.; Butler, B.W.; Ryan, K.C.; Gucker, C.L. 2012a. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Ecology. 93(4): 941–946. http://www.treesearch.fs.fed.us/pubs/41115. (3 March 2016).

Keane, R.E. 2013. Describing wildland surface fuel loading for fire management: a review of approaches, methods and systems. International Journal of Wildland Fire. 22: 51–62.

Keane, R.E. 2015. Wildland fuel fundamentals and applications. New York: Springer International Publishing. 191 p.

Keane, R.E.; Cary, G.J.; Flannigan, M.D.; Parsons, R.A.; Davies, I.D.; King, K.J.; Li, C.; Bradstock, R.A.; Gill, M. 2013. Exploring the role of fire, succession, climate, and weather on landscape dynamics using comparative modeling. Ecological Modelling. 266: 172–186.

Keane, R.E.; Gray, K.; Bacciu, V. 2012. Spatial variability of wildland fuel characteristics in northern Rocky Mountain ecosystems. Res. Pap. RMRS-RP-98. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 56 p.

Keane, R.E.; Herynk, J.M.; Toney, C.; Urbanski, S.P.; Lutes, D.C.; Ottmar, R.D. 2015. Assessing three fuel classification systems and their maps using Forest Inventory and Analysis (FIA) surface fuel measurements. In: Keane, R.E.; Jolly, W.M.; Parsons, R.; Riley, K. Proceedings, large wildland fires conference; 19–23 May, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 128–140.

Keane, R.E.; Karau, E. 2010. Evaluating the ecological benefits of wildfire by integrating fire and ecosystem simulation models. Ecological Modelling. 221: 1162–1172.

Keane, R.E.; Loehman, R. 2010. Understanding the role of wildland fire, insects, and disease in predicting climate change effects on whitebark pine: simulating vegetation, disturbance, and climate dynamics in a northern Rocky Mountain landscape [Abstract]. American Geophysical Union: fall meeting. https://www.treesearch.fs.fed.us/pubs/39331. (31 October 2016).

Keane, R.E.; Parsons, R.A. 2010. Restoring whitebark pine forests of the northern Rocky Mountains, USA. Ecological Restoration. 28(1): 56–70.

Keeley, J.E.; Aplet, G.H.; Christensen, N.L.; Conard, S.G.; Johnson, E.A.; Omi, P.N.; Peterson, D.L.; Swetnam, T.W. 2009. Ecological foundations for fire management in North American forest and shrubland ecosystems. Gen. Tech. Rep. PNW-GTR-779. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 92 p.

Kitchen, S.G. 2015. Climate and human influences on historical fire regimes (AD 1400–1900) in the eastern Great Basin (USA). The Holocene. doi:10.1177/0959683615609751.

Knapp, E.E.; Estes, B.L.; Skinner, C.N. 2009. Ecological effects of prescribed fire season: a literature review and synthesis for managers. Gen. Tech. Rep. PSW-GTR-224. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 80 p.

Koch, G.; Ager, A.; Kline, J.; Fischer, P. 2016. Polishing the prism: improving wildfire mitigation planning by coupling landscape and social dimensions. Science Findings 189. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 5 p.

Kovalev, V.; Petkov, A.; Wold, C.; Urbanski, S.; Hao, W.M. 2015. Determination of the smoke-plume heights and their dynamics with ground-based scanning LIDAR. Applied Optics. 54(8): 2011–2017.

Kramer, H.; Collins, B.; Kelly, M.; Stephens, S. 2014. Quantifying ladder fuels: a new approach using LiDAR. Forests. 5(6): 1432–1453.

Kremens, R.L.; Dickinson, M.B. 2015. Estimating radiated flux density from wildland fires using the raw output of limited bandpass detectors. International Journal of Wildland Fire. 24(4): 461–469.

Kremens, R.L.; Dickinson, M.B.; Bova, A.S. 2012. Radiant flux density, energy density, and fuel consumption in mixed-oak forest surface fires. International Journal of Wildland Fire. 21: 722–730.

Larkin, N.K.; Brown, T.; Lahm, P.; Zimmerman, T. 2010. Wildland fire decision support system air quality tools. Fire Management Today. 70(2): 36–40.

Larkin, N.K.; O'Neill, S.M.; Solomon, R.; Krull, C.; Raffuse, S.; Rorig, M.; Peterson, J.; Ferguson, S.A. 2009. The BlueSky smoke modeling framework. International Journal of Wildland Fire. 18: 906–920.

Larkin, N.K.; Raffuse, S.M.; Strand, T.M. 2014. Wildland fire emissions, carbon, and climate: U.S. emissions inventories. Forest Ecology and Management. 317: 61–69.

Lee, T.; Sullivan, A.P.; Mack, L.; Jimenez, J.L.; Kreidenweis, S.M.; Onasch, T.B.; Worsnop, D.R.; Malm, W.; Wold, C.E.; Hao, W.M.; Collett, J.L., Jr. 2010. Chemical smoke marker emissions during flaming and smoldering phases of laboratory open burning of wildland fuels. Aerosol Science and Technology. 44(9): i–v.

Lei, W.; Li, G.; Wiedinmyer, C.; Yokelson, R.J.; Molina, L.T. 2010. Model assessing the impact of biomass burning on air quality and photochemistry in Mexico City [Abstract]. American Geophysical Union: fall meeting.

Liljeblad, A.; Borrie, B.; Watson, A. 2010. Trust is a must: what is involved in trusting those who manage forest fires? Natural Inquirer. 13(1): 42–48.

Littell, J.S.; Peterson, D.L.; Riley, K.L.; Liu, Y.; Luce, C.H. 2016. A review of the relationships between drought and forest fire in the United States. Global Change Biology. doi:10.1111/gcb.13275.

Livingston, J. 2008. Small-diameter success stories III. Gen. Tech. Rep. FPL-GTR-175. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 31 p.

Loehman, R.A.; Clark, J.A.; Keane, R.E. 2011. Modeling effects of climate change and fire management on western white pine (*Pinus monticola*) in the northern Rocky Mountains, USA. Forests. Scientific Journal. 2: 832–860. https://www.fs.fed.us/rm/pubs_other/rmrs_2011_loehman_r001.pdf. (3 March 2017.)

Lorenz, T.J.; Aubry, C.; Shoal, R. 2008. A review of the literature on seed fate in whitebark pine and the life history traits of Clark's nutcracker and pine squirrels. Gen. Tech. Rep. PNW-GTR-742. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 62 p.

Lutes, D.C.; Keane, R.E.; Caratti, J.F. 2009. A surface fuel classification for estimating fire effects. International Journal of Wildland Fire. 18: 802–814.

Martinuzzi, S.; Stewart, S.I.; Helmers, D.P.; Mockrin, M.H.; Hammer, R.B.; Radeloff, V.C. 2015. The 2010 wildland-urban interface of the conterminous United States. Research Map NRS-8. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 124 p.

Massman, W.J. 2015. A non-equilibrium model for soil heating and moisture transport during extreme surface heating: the soil (heat-moisture-vapor) HMV-Model Version. Geoscientific Model Development. 8: 3659–3680.

McAllister, S. 2013. Critical mass flux for flaming ignition of wet wood. Fire Safety Journal. 61: 200–206.

McAllister, S.; Finney, M. 2013. Effect of crib dimensions on burning rate. In: Bradley, D.; Makhviladze, G.; Molkov, V.; Sunderland, P.; Tamanini, F., eds. Proceedings, 7th international seminar on fire and explosion hazards [ISFEH7]. College Park, MD: University of Maryland, Research Publishing. doi:10.3850/978-981-08-7724-8_0x-0x.

McAllister, S; Grenfell, I.; Hadlow, A.; Jolly, W.M.; Finney, M.; Cohen, J. 2012. Piloted ignition of live forest fuels. Fire Safety Journal. 51: 133–142.

McCaffrey, S. 2008. The homeowner view of thinning methods for fire hazard reduction: more positive than many think. In: Narog, M.G., ed. Proceedings, 2002 fire conference: managing fire and fuels in the remaining wildlands and open spaces of the Southwestern United States. Gen. Tech. Rep. PSW-GTR-189. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 15–22.

McCaffrey, S.M. 2015. Community wildfire preparedness: a global state-of-the-knowledge summary of social science research. Current Forestry Reports. 1(2): 81–90.

McCaffrey, S.M.; Olsen C.S. 2012. Research perspectives on the public and fire management: a synthesis of current social science on eight essential questions. Gen. Tech. Rep. NRS-104. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

McCaffrey, S.M.; Rhodes, A.; Stidham, M. 2015. Wildfire evacuation and its alternatives: perspectives from four United States' communities. International Journal of Wildland Fire. 24: 170–178.

McCaffrey, S.M.; Stidham, M.; Toman, E.; Shindler, B. 2011. Outreach programs, peer pressure, and common sense: what motivates homeowners to mitigate fire risk? Environmental Management. doi:10.1007/s00267-011-9704.

McIver, J.D.; Stephens, S.L.; Agee, J.K.; Barbour, J.; Boerner, R.E.J.; Edminster, C.B.; Erickson, K.L.; Farris, K.L.; Fettig, C.J.; Fiedler, C.E.; Haase, S.; Hart, S.C.; Keeley, J.E.; Knapp, E.E.; Lehmkuhl, J.F.; Moghaddas, J.J.; Otrosina, W.; Outcalt, K.W.; Schwilk, D.W.; Skinner, C.N.; Waldrop, T.A.; Weatherspoon, C.P.; Yaussy, D.A.; Youngblood, A.; Zack, S. 2012. Ecological effects of alternative fuel-reduction treatments: highlights of the National Fire and Fire Surrogate study. Journal of Wildland Fire. 21: 894–904.

McKenzie, D.; French, N.H.F.; Ottmar, R.D. 2012. National database for calculating fuel available to wildfires. Eos. 93(6): 57–58.

McKenzie, D.; Miller, C.; Falk D.A., eds. 2011. The landscape ecology of fire. Dordrecht, The Netherlands: Springer. 312 p.

McRae, D.J.; Conard, S.G.; Baker, S.P.; Samsonov, Y.N.; Ivanova, G.A. 2009. Fire emissions in central Siberia. The Canadian Smoke Newsletter. Fall: 9–13.

Mell, W.E.; Manzello, S.L.; Maranghides, A.; Butry, D.; Rehm, R.E.. 2010. The wildland–urban interface fire problem—current approaches and research needs. International Journal of Wildland Fire. 19: 238–251.

Metz, M.R.; Varner, J.M.; Frangioso, K.M.; Meentemeyer, R.K.; Rizzo, D.M. 2013. Collateral damage: fire and Phytophthora ramorum interact to increase mortality in coast redwood. In: Frankel, S.J.; Kliejunas, J.T.; Palmieri, K.M.; Alexander, J.M., tech. coords. Proceedings, sudden oak death fifth science symposium. Gen. Tech. Rep. PSW-GTR-243. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 65–66.

Miller, J.D.; Collins, B.M.; Lutz, J.A.; Stephens, S.L.; van Wagtendonk, J.W.; Yasuda, D.A. 2012. Differences in wildfires among ecoregions and land management agencies in the Sierra Nevada region, California, USA. Ecosphere. 3(9): 80.

Miller, J.D.; Skinner, C.N.; Safford, H.D.; Knapp, E.E.; Ramirez, C.M. 2012. Trends and causes of severity, size, and number of fires in northwestern California. Ecological Applications 22(1): 184–203.

Miller, M.E.; MacDonald, L.H.; Robichaud, P.R.; Elliot, W.J. 2011. Predicting post-fire hillslope erosion in forest lands of the Western United States. International Journal of Wildland Fire. 20(8): 982–999. doi:10.1071/WF09142.

Moody, J.A.; Shakesby, R.A.; Robichaud, P.R.; Cannon, S.H.; Martin, D.A. 2013. Current research issues related to post-wildfire runoff and erosion processes. Earth-Science Reviews. 122: 10–37. doi:10.1016/J.EAR SCIREV.2013.03.004.

Morgan, P.; Hardy, C; Swetnam, T.W.; Rollins, M.G.; Long, D.G. 2001. Mapping fire regimes across time and space: understanding coarse and fine scale fire patterns. International Journal of Wildland Fire. 10: 329–342. doi:10.1071/WF01032.

Morgan, P.; Heyerdahl, E.K.; Miller, C.; Wilson, A.M.; Gibson, C.E. 2014. Northern Rockies pyrogeography: an example of fire atlas utility. Fire Ecology. 10(1): 14–30.

Morrow, C.D.; Gorman, T.M.; Evans, J.W.; Kretschmann, D.E.; Hatfield, C.A. 2013. Prediction of wood quality in small-diameter Douglas-fir using site and stand characteristics. Wood and Fiber Science. 45(1): 49–61.

Murphy, D.; Wyborn, C.; Yung, L.; Williams, D.R.; Cleveland, C.; Eby, L.; Dobrowski, S.; Towler, E. 2016. Engaging communities and climate change futures with Multi-Scale, Iterative Scenario Building (MISB) in the Western United States. Human Organization. 75(1): 33–46.

Murphy, D.J.; Wyborn, C.; Yung, L.; Williams, D.R. 2015. Key concepts and methods in social vulnerability and adaptive capacity. Gen. Tech. Rep. RMRS-GTR-328. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 24 p.

National Science and Technology Council [NSTC]. 2015. Wildland fire science and technology task force final report. http://www.sdr.gov/docs/185820_Wildfire_FINAL.pdf. (31 October 2016).

Neary, D.G.; Haase, S.M.; Overby, S.T. 2008. Total carbon and nitrogen in mineral soil after 26 years of prescribed fire: Long Valley and Fort Valley Experimental Forests. In: Olberding, S.D.; Moore, M.M., tech coords. Proceedings, Fort Valley Experimental Forest—a century of research 1908–2008 conference; 7–9 August; Flagstaff, AZ. Proceedings RMRS-P-53CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 305–312.

Neary, D.G.; Ryan, K.C.; DeBano, L.F., eds. 2005. Wildland fire in ecosystems: effects of fire on soils and water. Gen. Tech. Rep. RMRS-GTR-42. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p. Vol. 4.

Negron, J.F.; Bentz, B.J.; Fettig, C.J.; Gillette, N.; Hansen, E.M.; Hayes, J.L.; Kelsey, R.G.; Lundquist, J.E.; Lynch, A.M.; Progar, R.A.; Seybold, S.J. 2008. U.S. Forest Service bark beetle research in the Western United States: looking toward the future. Journal of Forestry. 106(6): 325–331.

Noonan-Wright, E.K.; Opperman, T.S. 2015. Applying the Wildland Fire Decision Support System (WFDSS) to support risk-informed decision making: the Gold Pan Fire, Bitterroot National Forest, Montana, USA. In: Keane, R.E.; Jolly, M.; Parsons, R.; Riley, K. Proceedings, large wildland fires conference; 19–23 May, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 320–323.

Noonan-Wright, E.; Opperman, T.S.; Finney, M.A.; Zimmerman, G.T.; Seli, R.C.; Elenz, L.M.; Calkin, D.E.; Fiedler, J.R. 2011. Developing the U.S. Wildland Fire Decision Support System. Journal of Combustion. 2011: 168473. 14 p.

North, M.P.; Collins, B.M.; Stephens, S.L. 2012. Using fire to increase the scale, benefits and future maintenance of fuels treatments. Journal of Forestry. 110(7): 392–401.

O'Callaghan, J.; Fischer, A.P.; Charnley. S. 2013. Managing wildfire risk in fire-prone landscapes: how are private landowners contributing? Science Findings 154. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 6 p.

O'Connor, C.D.; Falk, D.A.; Lynch, A.M.; Swetnam, T.W. 2014. Fire severity, size, and climate associations diverge from historical precedent along an ecological gradient in the Pinaleño Mountains, Arizona, USA. Forest Ecology and Management. 329: 264–278.

O'Connor, C.D.; Thompson, M.P.; Rodriguez y Silva, F. 2016. Getting ahead of the wildfire problem: quantifying and mapping management challenges and opportunities. Geosciences. 6(3): 35.

Olsen, C.S.; Mallon, A.L.; Shindler, B.A. 2012. Public acceptance of disturbance-based forest management: factors influencing support. ISRN Forestry. 10 p, doi:10.5402/2012/594067.

Ottmar, R.D.; Burns, M.F.; Hall, J.N.; Hanson, A.D. 1993. CONSUME: users guide. Gen. Tech. Rep. PNW-GTR-304. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 120 p.

Parks, S.A.; Miller, C.; Holsinger, L.M.; Baggett, L.S.; Bird, B.J. 2016. Wildland fire limits subsequent fire occurrence. International Journal of Wildland Fire. 25: 182–190.

Parks, S.A.; Miller, C.; Nelson, C.R.; Holden, Z.A. 2014. Previous fires moderate burn severity of subsequent wildland fires in two large western U.S. wilderness areas. Ecosystems. 17: 29–42.

Parsons, R.A. 2006. FUEL3-D: a spatially explicit fractal fuel distribution model. In: Andrews, P.L.; Butler, B.W., comps. Proceedings, fuels management—how to measure success; 28–30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 253–272.

Parsons, R.A.; Mell, W.; McCauley, P. 2010. Modeling the spatial distribution of forest crown biomass and effects on fire behavior with FUEL3D and WFDS. In: Viegas, D.X., ed. Proceedings, 6th international conference on forest fire research; 15–18 November; Coimbra, Portugal: University of Coimbra. 15 p.

Parsons, R.A.; Mell, W.E.; McCauley, P. 2011. Linking 3D spatial models of fuels and fire: effects of spatial heterogeneity on fire behavior. Ecological Modelling. 222: 679–691.

Paveglio, T.B.; Moseley, C.; Carroll, M.S.; Williams, D.R.; Davis, E.J.; Fischer, A.P. 2015. Categorizing the social context of the wildland urban interface: adaptive capacity for wildfire and community "archetypes." Forest Science. 61(2): 298–310.

Peterson, D.L.; Evers, L.; Gravenmier, R.A.; Eberhardt, E. 2007. A consumer guide: tools to manage vegetation and fuels. Gen. Tech. Rep. PNW-GTR-690. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 151 p.

Peterson, D.L.; Hardy, C.C. 2016. The RxCADRE study: a new approach to interdisciplinary fire research. International Journal of Wildland Fire. 25: i.

Pickett, B.M.; Isackson, C.; Wunder, R.; Fletcher, T.H.; Butler, B.W.; Weise, D.R. 2010. Experimental measurements during combustion of moist individual foliage samples. International Journal of Wildland Fire. 19(2): 153–162.

Pierce, K.B., Jr.; Ohmann, J.L.; Wimberly, M.C.; Gregory, M.J.; Fried, J.S. 2009. Mapping wildland fuels and forest structure for land management: a comparison of nearest neighbor imputation and other methods. Canadian Journal of Forestry Research. 39: 1901–1916.

Pollina, J.B.; Colle, B.A.; Charney, J.J. 2013. Climatology and meteorological evolution of major wildfire events over the Northeast United States. Weather Forecasting. 28: 175–193.

Preisler, H.K.; Ager, A.A.; Hayes, J.L. 2010. Probabilistic risk models for multiple disturbances: an example of forest insects and wildfires. In: Pye, J.M.; Rauscher, H.M.; Sands, Y.; Lee, D.C.; Beatty, J.S., tech. eds. Advances in threat assessment and their application to forest and rangeland management. Gen. Tech. Rep. PNW-GTR-802. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest and Southern Research Stations: 371–379.

Preisler, K.; Schweizer, D.; Cisneros, R.; Procter, T.; Ruminski, M.; Tarnay, L. 2015. A statistical model for determining impact of wildland fires on Particulate Matter ($PM_{2.5}$) in central California aided by satellite imagery of smoke. Environmental Pollution. 205: 340–349.

Prichard, S.J.; Peterson, D.L.; Jacobson, K. 2010. Fuel treatments alter the effects of wildfire in dry mixed conifer forest, north-central Washington, USA. Canadian Journal of Forest Research. 40: 1615–1626.

Prichard, S.J.; Sandberg, D.V.; Ottmar, R.D.; Eberhardt, E.; Andreu, A.; Eagle, P.; Swedin, K.L. 2013. Fuel Characteristic Classification System version 3.0: technical documentation. Gen. Tech. Rep. PNW-GTR-887. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 79 p.

Pyne, S.J. 2013. Enough is enough: trying fires. Fire Safe Montana. http://firesafemt.org/enough-is-enough-trying-fires-by-stephen-pyne. (1 October 2016).

Reeves, M.C.; Ryan, K.C.; Rollins, M.G.; Thompson, T.G. 2009. Spatial fuel data products of the LANDFIRE project. International Journal of Wildland Fire. 18: 250–267.

Reinhardt, E. 2005. Fuels planning: science synthesis and integration; environmental consequences fact sheet 09: Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Res. Note RMRS-RN-23-9WWW. Fort Collins, CO: U.S. Department of Agriculture, Rocky Mountain Research Station. 2 p.

Reinhardt, E.; Lutes, D.; Scott, J. 2006a. FuelCalc: a method for estimating fuel characteristics. In: Andrews, P.L.; Butler, B.W., comps. Proceedings, fuels management—how to measure success. 28–30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 273–282.

Reinhardt, E.; Scott, J.; Gray, K.; Keane, R. 2006b. Estimating canopy fuel characteristics in five conifer stands in the Western United States using tree and stand measurements. Canadian Journal of Forest Research. 36: 2803–2814.

Reynolds, R.T.; Sanchez Meador, A.J.; Youtz, J.A.; Nicolet, T.; Matonis, M.S.; Jackson, P.L.; DeLorenzo, D.G.; Graves, A.D. 2013. Restoring composition and structure in southwestern frequent-fire forests: a science-based framework for improving ecosystem resiliency. Gen. Tech. Rep. RMRS-GTR-310. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 76 p.

Riccardi, C.L.; Prichard, S.J.; Sandberg, D.V.; Ottmar, R.D. 2007. Quantifying physical characteristics of wildland fuels using the fuel characteristic classification system. Canadian Journal of Forestry Research. 37: 2413–2420.

Robert, L.; Smith, A.M.S.; Dickinson, M.B. 2010. Fire metrology: current and future directions in physics-based measurements. Fire Ecology. 6(1): 13–35.

Robichaud, P.R.; Ashmun, L.E.; Sims, B.D. 2010. Post-fire treatment effectiveness for hillslope stabilization. Gen. Tech. Rep. RMRS-GTR-240. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 62 p.

Robichaud, P.R.; Wagenbrenner, J.W.; Pierson, F.B.; Spaeth, K.E.; Ashmun, L.E.; Moffet, C.A. 2016. Infiltration and interrill erosion rates after a wildfire in western Montana, USA. Catena. 142: 77–88.

Rollins, M.G. 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. International Journal of Wildland Fire. 18(3): 235–249.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station. 40 p.

Ryan, K.C.; Opperman, T.S. 2013. LANDFIRE—a national vegetation/fuels data base for use in fuels treatment, restoration, and suppression planning. Forest Ecology and Management. 294: 208–216.

Ryan, K.C.; Rigolot, E.; Rego, F.C.; Botelho, H.; Vega, J.A.; Fernandes, P.M.; Sofronova, T.M. 2010. Use of prescribed burning for restoration and maintenance of ecological conditions: predicting and managing fire injury and tree mortality. In: Proceedings, 7th European conference on ecological restoration; 23–27 August 2010; Avignon, France. Washington, DC: Society for Ecological Restoration International. 4 p.

Saab, V.A.; Powell, H.D.W.; Kotliar, N.B.; Newlon, K.R. 2005. Variation in fire regimes of the Rocky Mountains: implications for avian communities and fire management. In: Saab, V.; Powell, H., eds. Fire and avian ecology in North America. Studies in Avian Biology. 30: 76–96.

Sachdeva, S; McCaffrey, S.; Locke, D. 2016. Social media approaches to modeling wildfire smoke dispersion: spatiotemporal and social scientific investigations. Information, Communication & Society. 16 p. http://dx.doi.org/10.1080/1369118X.2016.1218528. (3 March 2017).

Sample, V.A.; Halofsky, J.E.; Peterson, D.L. 2014. U.S. strategy for forest management adaptation to climate change: building a framework for decision making. Annals of Forest Science. 71(2): 125–130.

Schwilk, D.W.; Keeley, J.E.; Knapp, E.E.; Mciver, J.; Bailey, J.D.; Fettig, C.J.; Fiedler, C.E.; Harrod, R.J.; Moghaddas, J.J.; Outcalt, K.W.; Skinner, C.N.; Stephens, S.L.; Waldrop, T.A.; Yaussy, D.A.; Youngblood, A. 2009. The national fire and fire surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecological Applications. 19(2): 285–304.

Scott, A.C.; Bowman, D.M.J.S.; Bond, W.J.; Pyne, S.J.; Alexander, M.E. eds. 2014. Fire on Earth: an introduction. Chichester, United Kingdom: John Wiley and Sons. 434 p.

Scott, J.H.; Burgan, R.E. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.

Skinner, C.; Abbott, C.; Fry, D.; Stephens, S.; Taylor, A.; Trouet, V. 2009. Human and climatic influences on fire occurrence in California's North Coast Range. Fire Ecology. 5(3): 76–99.

Smith, D.M. 2012. The Missoula Fire Sciences Laboratory: a 50-year dedication to understanding wildlands and fire. Gen. Tech. Rep. RMRS-GTR-270. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 62 p.

Sommers, W.T.; Loehman, R.A.; Hardy, C.C. 2014. Wildland fire emissions, carbon, and climate: science overview and knowledge needs. Forest Ecology and Management. 317: 1–8.

Steelman, T.A.; McCaffrey, S.M.; Velez, A.K.; Briefel, J.A. 2015. What information do people use, trust, and find useful during a disaster? Evidence from five large wildfires. Natural Hazards. 76(1): 615–634.

Stein, S.M.; Menakis, J.; Carr, M.A.; Comas, S.J.; Stewart, S.I.; Cleveland, H.; Bramwell, L.; Radeloff, V.C. 2013. Wildfire, wildlands, and people: understanding and preparing for wildfire in the wildland-urban interface—a Forests on the Edge report. Gen. Tech. Rep. RMRS-GTR-299. Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 36 p.

Stonesifer, C.S.; Calkin, D.E.; Thompson, M.P.; Kaiden, J.D. 2014. Developing an aviation exposure index to inform risk-based fire management decisions. Journal of Forestry. 112(6): 581–590.

Strand, T.; Gullett, B.; Urbanski, S.; O'Neill, S.; Potter, B.; Aurell, J.; Holder, A.; Larkin, N.; Moore, M.; Rorig, M. 2016. Grassland and forest understorey biomass emissions from prescribed fires in the Southeastern United States - RxCADRE 2012. International Journal of Wildland Fire. 25: 102–113.

Stueve, K.M.; Cerney, D.L.; Rochefort, R.M.; Kurth, L.L. 2009. Post-fire tree establishment patterns at the alpine treeline ecotone: Mount Rainier National Park, Washington, USA. Journal of Vegetation Science. 20(1): 107–120.

Sturtevant, B.R.; Miranda, B.R.; Wolter, P.T.; James, P.M.A.; Fortin, M.; Townsend, P.A. 2014. Forest recovery patterns in response to divergent disturbance regimes in the Border Lakes region of Minnesota (USA) and Ontario (Canada). Forest Ecology and Management. 313: 199–211.

Sturtevant, V.; Jakes, P. 2008. Collaborative planning to reduce risk. In: Martin, W.E.; Raish, C.; Kent, B., eds. Wildfire risk human perceptions and management implications. Washington, DC: Resources for the Future: 44–63.

Sturtevant, V.; Myer, G. 2013. Fire up: youth working with communities to adapt to wildfire. Res. Note NRS-163. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 20 p.

Thomas-Van Gundy, M.A.; Nowacki, G.J. 2013. The use of witness trees as pyro-indicators for mapping past fire conditions. Forest Ecology and Management. 304: 333–344.

Thompson, M.P. 2013. Modeling wildfire incident complexity dynamics. PLOS ONE. 8(5): e63297. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0063297. (3 March 2017).

Thompson, M.P.; Haas, J.R.; Gilbertson-Day, J.W.; Scott, J.H.; Langowski, P.; Bowne, E.; Calkin, D.E. 2015. Development and application of a geospatial wildfire exposure and risk calculation tool. Environmental Modelling and Software. 63: 61–72.

Thompson, M.P.; Hand, M.S.; Gilbertson-Day, J.W.; Vaillant, N.M.; Nalle, D.J. 2013. Hazardous fuel treatments, suppression cost impacts, and risk mitigation. In: González-Cabán, A., tech. coord. Proceedings, 4th international symposium on fire economics, planning, and policy: climate change and wildfires. Gen. Tech. Rep. PSW-GTR-245 (English). Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 66–80.

Thompson, M.P.; MacGregor, D.G.; Calkin, D.E. 2016. Risk management: core principles and practices, and their relevance to wildland fire. Gen. Tech. Rep. RMRS-GTR-350. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 29 p.

Toman, E.; Shindler, B.; McCaffrey, S.; Bennett, J. 2014. Public acceptance of wildland fire and fuel management: Panel responses in seven locations. Environmental Management. 54(3): 557–570.

Trotter, T. 2013. Relationships among climate, forests, and insects in North America: examples of the importance of long-term and broad-scale perspectives. In: Camp, A.E.; Irland, L.C.; Carroll, C.J.W. Long-term silvicultural and ecological studies: results for science and management. GISF Res. Pap. 013. New Haven, CT: Yale University, School of Forestry and Environmental Studies, Global Institute of Sustainable Forestry: 161–177. Volume 2.

Trouet, V.; Taylor, A.H.; Wahl, E.R.; Skinner, C.N. 2010. Fire-climate interactions in the American West since 1400 CE. Geophysical Research Letters. 37: L04702.

Urbanski, S.P.; Hao, W.M.; Nordgren, B. 2011. The wildland fire emission inventory: Western United States emission estimates and an evaluation of uncertainty. Atmospheric Chemistry and Physics. 11: 12973–13000.

U.S. Department of Agriculture [USDA] Forest Service. 2006. Wildland fire and fuels research and development strategic plan: meeting the needs of the present, anticipating the needs of the future. Washington, DC: U.S. Department of Agriculture, Forest Service, Research and Development. 50 p.

USDA Forest Service. 2015a. USDA Forest Service strategic plan: FY 2015–2020. FS-105. 53 p. http://www.fs.fed.us/strategicplan. (1 October 2016).

USDA Forest Service. 2015b. The rising cost of fire operations: effects on the Forest Service’s non-fire work. 16 p. http://www.fs.fed.us/sites/default/files/2015-Fire-Budget-Report.pdf. (1 October 2016).

USDA Forest Service and U.S. Department of the Interior [DOI]. 2014a. The national strategy: the final phase of the National Cohesive Wildland Fire Management Strategy. https://www.forestsandrangelands.gov/strategy/documents/strategy/CSPhaseIIINationalStrategyApr2014.pdf. (1 October 2016).

USDA Forest Service and DOI. 2014b. 2014 quadrennial fire review (QFR) final report. 87 p. https://www.forestsandrangelands.gov/QFR/documents/2014QFR-FinalReport.pdf. (1 October 2016).

Vaillant, N.M.; Ager, A.A. 2014. ArcFuels: an ArcMap toolbar for fuel treatment planning and wildfire risk assessment. Fire Management Today. 74(1): 21–23.

Vaillant, N.M.; Ager, A.A.; Anderson, J. 2013. ArcFuels10 system overview. Gen. Tech. Rep. PNW-GTR-875. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 65 p.

Vaillant, N.M.; Ager, A.A.; Anderson, J.; Miller, L. 2013. ArcFuels User Guide and Tutorial: for use with ArcGIS 9. Gen. Tech. Rep. PNW-GTR-877. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 256 p.

Vaillant, N.M.; Noonan-Wright, E.K.; Reiner, A.L.; Ewell, C.M.; Rau, B.M.; Fites-Kaufman, J.A.; Dailey, S.N. 2015. Fuel accumulation and forest structure change following hazardous fuel reduction treatments throughout California. International Journal of Wildland Fire. 24: 361–371. http://dx.doi.org/10.1071/WF14082. (3 March 2017).

Wang, W.J.; He, H.S.; Spetich, M.A.; Shifley, S.R.; Thompson, F.R., III; Larsen, D.R.; Fraser, J.S.; Yang, J. 2013. A large-scale forest landscape model incorporating multi-scale processes and utilizing forest inventory data. Ecosphere. 4(9): 1–22.

Werth, P.A.; Potter, B.E.; Alexander, M.E.; Clements, C.B.; Cruz, M.G.; Finney, M.A.; Forthofer, J.M.; Goodrick, S.L.; Hoffman, C.; Jolly, W.M.; McAllister, S.S.; Ottmar, R.D.; Parsons, R.A. 2016. Synthesis of knowledge of extreme fire behavior: volume 2 for fire behavior specialists, researchers, and meteorologists. Gen. Tech. Rep. PNW-GTR-891. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 258 p.

White, R.H.; Sumathipala, K. 2013. Cone calorimeter tests of wood composites. In: Proceedings, fire and materials 2013 conference; 28–30 January; San Francisco, CA: 401–412. https://www.fpl.fs.fed.us/documnts/pdf2013/fpl_2013_white002.pdf. (3 March 2017).

Williams, D.R.; Jakes, P.J.; Burns, S.; Cheng, A.S.; Nelson, K.C.; Sturtevant, V.; Brummel, R.F.; Staychock, E.; Souter, S.G. 2012. Community wildfire protection planning: the importance of framing, scale, and building sustainable capacity. Journal of Forestry. 110(8): 415–420.

Winandy, J.E. 2006. Advanced wood- and bio-composites: enhanced performance and sustainability. In: Advanced materials and processing IV: selected, peer reviewed papers presented at the 4th international conference on advanced materials and processing; 10–13 December; Hamilton, New Zealand. Zurich: Trans Tech Publications: 9–14. https://www.fpl.fs.fed.us/documnts/pdf2006/fpl_2006_winandy002.pdf. (3 March 2017).

Winter, P.L.; Long, J.W.; Lake, F.K. 2014. Sociocultural perspectives on threats, risks, and health. In: Long, J.W.; Quinn-Davidson, L.; Skinner, C.N., eds. Science synthesis to support socioecological resilience in the Sierra Nevada and southern Cascade Range. Gen. Tech. Rep. PSW-GTR-247. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 569–598. Chapter 9.3.

Woodsmith, R.D.; Vache, K.B.; McDonnell, J.J. 2007. The Entiat Experimental Forest: a unique opportunity to examine hydrologic response to wildfire. In: Furniss, M.J.; Clifton, C.; Ronnenberg, K.L., eds. Advancing the fundamental sciences: proceedings of the Forest Service national earth sciences conference. Portland, OR: U.S. Department of Agricultire, Forest Service, Pacific Northwest Research Station: 205–216.

Yashwanth, B.L.; Shotorban, B.; Mahalingam, S.; Weise, D.R. 2015. An investigation of the influence of heating modes on ignition and pyrolysis of woody wildland fuel. Combustion Science and Technology. 187(5): 780–796.

Yi, S.; McGuire, A.D.; Kasischke, E.; Harden, J.; Manies, K.; Mack, M.; Turetsky, M. 2010. A dynamic organic soil biogeochemical model for simulating the effects of wildfire on soil environmental conditions and carbon dynamics of black spruce forests. Journal of Geophysical Research. 115(G04015): 15.

Zhu, J.Y.; Zhang, C.; Gleisner, R.; Houtman, C.J.; Pan, X. 2016. Bioconversion of woody biomass to biofuel and lignin co-product using sulfite pretreatment to overcome the recalcitrance of lignocelluloses (SPORL). Gen. Tech. Rep. FPL-GTR-240. Washington, DC: U.S. Department of Agricultire, Forest Service, Forest Products Laboratory. 34 p.

Zimmerman, T.; Lasko, R.; Kaufmann, M. 2014. Fuel treatment science plan. Boise, ID: Joint Fire Science Program. 67 p. http://www.firescience.gov/documents/fuels/FTSP_093014_v3.pdf. (1 October 2016).

## APPENDIX A

# Organization and Program Components

The Wildland Fire and Fuels program is one of the seven major Research and Development (R&D) Strategic Program Areas (SPAs) in the Forest Service, an agency of the U.S. Department of Agriculture. The R&D Wildland Fire and Fuels program provides fundamental understanding of fire processes, fire/ecosystem interactions, and the social and economic aspects of fire management. The program also provides knowledge and products that support operation in the four key areas of the National Fire Plan (NFP) and meet the goals of the Healthy Forests Restoration Act of 2003. Research is focused on assessing fire behavior and risk; modeling smoke; improving the characterization of fuels; identifying the effects of fire and fuel treatments on ecosystem components and processes, as well as water and air quality; distinguishing the interactions between fire and climatic patterns; understanding the social factors that affect community interactions and decisionmaking, as well as the economics of fire and fuel management; characterizing the effectiveness of hazardous fuels treatments; identifying opportunities for biomass utilization; developing products from traditionally underused wood sources; integrating information from all areas into an improved understanding and modeling of landscape-scale management and impacts; and improving the application of science to meet management needs.

One of the most rapidly changing areas of wildland fire research is science delivery. Although refereed publications will always be the foundation of science delivery, all levels of the Forest Service are placing increased emphasis on new methods for getting research information and tools into the hands of those who need to use them. As a result of these activities and trends, the R&D Wildland Fire and Fuels program continues to be responsive to changing needs and on the leading edge of developing knowledge and tools to support sound decisions.

The R&D Wildland Fire and Fuels program is carried out in 39 research groups, distributed across all of the five research stations, the Forest Products Laboratory (FPL), and the International Institute of Tropical Forestry. Three Forest Service research laboratories are devoted primarily to wildland fire and fuels R&D: the Rocky Mountain Research Station's (RMRS) Missoula Fire Sciences Laboratory in Missoula, MT (http://www.firelab.org/); the Pacific Southwest Research Station's Fire Sciences Laboratory in Riverside, CA (http://www.fs.fed.us/psw/rfl); and the Pacific Northwest Research Station's Pacific Wildland Fire Sciences Laboratory in Seattle, WA (http://www.fs.fed.us/pnw/pwfsl/). In addition to work conducted at these laboratories, all research stations and the FPL have significant programs or research work units that carry out fire research. In 2006, the Forest Service established a national Wildland Fire Management Research, Development, and Applications (RD&A) program at

RMRS and the National Interagency Fire Center (http://www.nifc.gov/) in Boise, ID. External collaborators play a critical role in much of this R&D.

The R&D Wildland Fire and Fuels program is unique among Forest Service R&D programs in that the research is currently supported broadly out of three separately appropriated programs: (1) Forest Service R&D, (2) the National Fire Plan Research and Development Program (NFP R&D), and (3) the Joint Fire Science Program (JFSP). Although each of these programs has different goals, the priorities and processes are complementary.

**The Forest Service R&D appropriation (base funding)** has provided a foundation for the long-term scientific capacity, facilities, and research accomplishments since the early 1900s. This funding supports most of the R&D Wildland Fire and Fuels program's permanent research staff; maintains the experimental facilities, offices, and other infrastructure; and provides the essential core capacity on which staff build with funds from other sources. The program has a rich history in the Forest Service, the most successful periods of which have often resulted from partnerships with the fire management community (e.g., the FireScope RD&A program in the 1970s, which led to development of the Incident Command System now used around the world for disaster response). Program priorities for Forest Service R&D are established by the R&D deputy staff and the research stations in consultation with the end users of the products of wildland fire and fuels research, stakeholders, and collaborators within and outside the Federal Government. Since 2006, the R&D Wildland Fire and Fuels program budget formulation and reporting have been carried out in the context of the Wildland Fire and Fuels R&D Strategic Plan. To track trends over time, stations have developed retrospective classification of their programs and outputs in R&D Wildland Fire and Fuels portfolios from 2000 to the present.

**The Joint Fire Science Program** (http://www.firescience.gov/) was created by Congress in 1998 as an interagency research, development, and science application partnership between the U.S. Department of the Interior (DOI) and the Forest Service. Program oversight is provided by a governing board, which includes representatives from five DOI agencies and the Forest Service with diverse backgrounds in R&D, fire management, and land management. JFSP supports research, tool development, and science application related to the following specific emphasis areas defined by Congress: fuel inventory and mapping; fuel treatment scheduling and risk assessment; fire effects and behavior; monitoring and evaluation; restoration of fire-adapted ecosystems; postfire stabilization, rehabilitation, and restoration; remote sensing; and developing and integrating research information for local land managers.

The JFSP funds individual research and science application projects for periods of up to 3 years. Projects are selected for funding through a rigorous peer review process. The program has funded 571 research studies that finished between 1998 and 2016 and 304 ongoing research projects from 2010 to 2016. On average, about 20 percent of the proposals received are funded. More than 90 colleges and universities, and numerous other partners, have collaborated on JFSP-sponsored research projects. The JFSP has a strong focus on management agency involvement and science application to ensure that managers are aware of, understand, and can use the research results to make sound decisions and implement projects.

**The National Fire Plan Research and Development Program** was initiated in 2001 to conduct R&D activities in support of the four main goals of the NFP: (1) firefighting capacity, (2) rehabilitation and restoration, (3) hazardous fuel reduction, and (4) community assistance. The initial program was established through a competitive process internal to the Forest Service. As a result of this process, in 2001 and 2002, 78 research teams were established across the country, spread across the four key NFP areas. By the end of fiscal year 2006, the NFP had met all of its initial funding commitments. The current allocation process responds to the priorities outlined in the Wildland Fire and Fuels R&D Strategic Plan. With guidance from the strategic plan, and recommendations of the Wildland Fire and Fuels R&D portfolio teams and SPA team, NFP R&D continues to address NFP priorities in the four key areas:

- Firefighting capacity: Providing better models of weather, fire behavior, smoke, and other tools for improving firefighter decisions.
- Rehabilitation and restoration: Providing rapid response information and models to help restore landscapes and protect communities from the aftereffects of fire.
- Hazardous fuel reduction: Developing improved analysis tools for determining the effects and economic tradeoffs of treatments intended to reduce fire risk by removing hazardous fuels.
- Community assistance: Working with communities to understand their needs and priorities, develop new approaches and materials for education, and recommend acceptable approaches to ensure adequate community protection from wildfire.

Even though each of the program components described here has a slightly different emphasis and function, in practice the four work together in a complementary fashion. Many lines of work in wildland fire and fuels R&D receive support from all three appropriated programs; most of our active research is supported by NFP R&D or JFSP in addition to the base R&D Wildland Fire and Fuels program funding (figure 1).

## External Funding

Additional research funding comes from external competitive grants or other programs in partner agencies such as the National Aeronautics and Space Administration (NASA) and U.S. Environmental Protection Agency (EPA). National Science Foundation regulations generally prohibit the funding of Federal researchers. As science makes the transition from research into application and, eventually, operational use, operational budgets in the Forest Service, DOI, and other agencies increasingly provide funding support for wildland fire and fuels R&D. For example, projects involving the development of the National Fire Danger Rating System, the implementation of seasonal fire severity forecasts for integrated response protocols, the development of a model that predicts fire spread probability (FSPro), the development of national data layers needed for modeling values at risk from wildfire (LANDFIRE), and R&D involvement in development of the Wildland Fire Decision Support System (WFDSS) are supported as special projects by Forest Service State and Private Forestry.

The importance of these other sources of funding is clear when looking at the proportion of the base R&D appropriation to other funding areas that currently support salaries of permanent employees (figure 1). Other fixed costs, such as facility maintenance, have also increased in the last 8 years. In some units, salaries and other fixed costs may account for more than 95 percent of the budget. The real costs of conducting state-of-the art research, including the costs of renovating facilities and providing up-to-date laboratory equipment and field instrumentation (e.g., for quantification of fire behavior, smoke dispersion, or windflow patterns), have also increased.

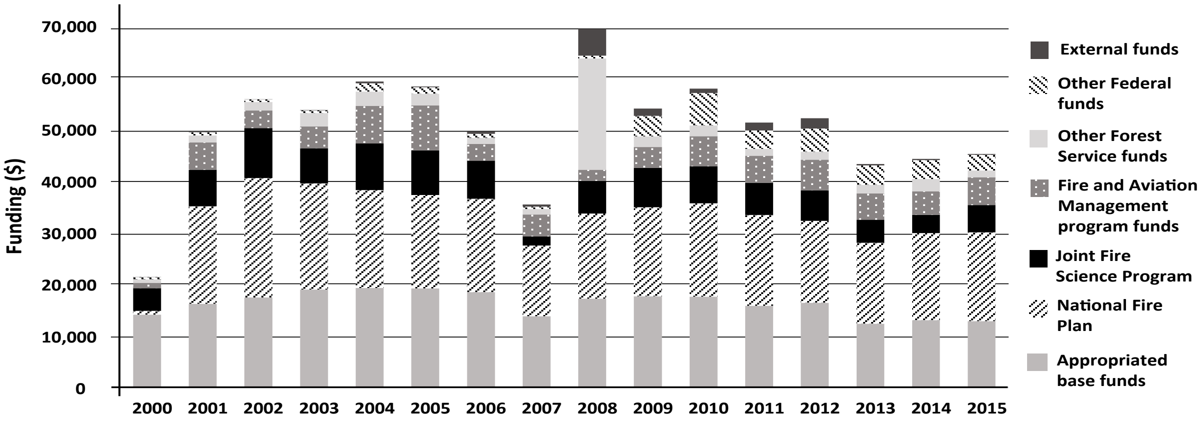
To overcome these resource and capacity obstacles, Forest Service R&D builds programs by clearly articulating research needs, developing consensus, and engaging stakeholders to formulate plans and strengthen partnerships. This process includes collaborating with other deputy areas and agencies on funding and encouraging scientists to actively compete for internal and external funding.

## Staffing

In 2015, 117 scientists conducted wildland fire and fuels research, development, and science applications nationwide. Since 2000, the total number of scientific staff working on wildland fire and fuels R&D increased 162 percent. The number of Research Grade Evaluation scientists (scientists whose grade level is determined using the Office of Personnel Management's Research Grade Evaluation Guide) working on wildland fire R&D increased 45 percent, from 63 scientists in 2000 to 117 scientists in 2015 (figure 2). At 100 employees, the number of professional and technical support staff has been stable since the 2000-to-2015 period.

This situation most likely reflects a decrease in the number of temporary employees working on The Wildland Fire and Fuels R&D Program and a lack of replacement employees for some of the permanent employees who have left or retired, as funds available for the program R&D have fluctuated over that time period.

**Figure 1.** Forest Service Research and Development funding for the Wildland Fire and Fuels program by source of funding.



The grade-level distribution of scientific and technical staff working on wildland fire R&D is shown in figure 3. This graph does not include any staff at grade levels lower than GS-7, which means that some student and summer temporary employees are not shown. It is worth noting, however, that the number of technical staff at the lower grade levels (GS-7 and GS-9) has mostly been decreasing since 2003 and 2004. The decrease may reflect either overall reductions in personnel or assignment of staff to other research areas as funding for the R&D Wildland Fire and Fuels program has fluctuated since 2000 (figure 1). On the other hand, the number of staff at higher grade levels (GS-14 and GS-15) either remained fairly constant or increased between 200 and 2015, and staff at the highest grade level (GS-16) were added in 2013. The trends for staff at higher grade levels are most likely a reflection of the promotion of permanent scientists for whom grade level is based on performance and on complexity of research assignment under the Research Grade Evaluation Guide, which involves a peer review process similar to faculty evaluation systems used by universities. Research Grade Evaluation scientists are generally considered to be performing at an equivalent level to tenured research faculty (associate or full professors) at a major university.

**Figure 2.** Full-time equivalent staffing of scientists, professionals, and technical staff working on fire-related research from 2000 through 2015. The data for scientists include permanent scientists, as well as postdoctoral scientists classified under the Research Grade Evaluation Guide. Research Grade scientists are evaluated periodically, and the grade is determined by research assignment, supervisory controls, originality, contributions, impact, and stature.

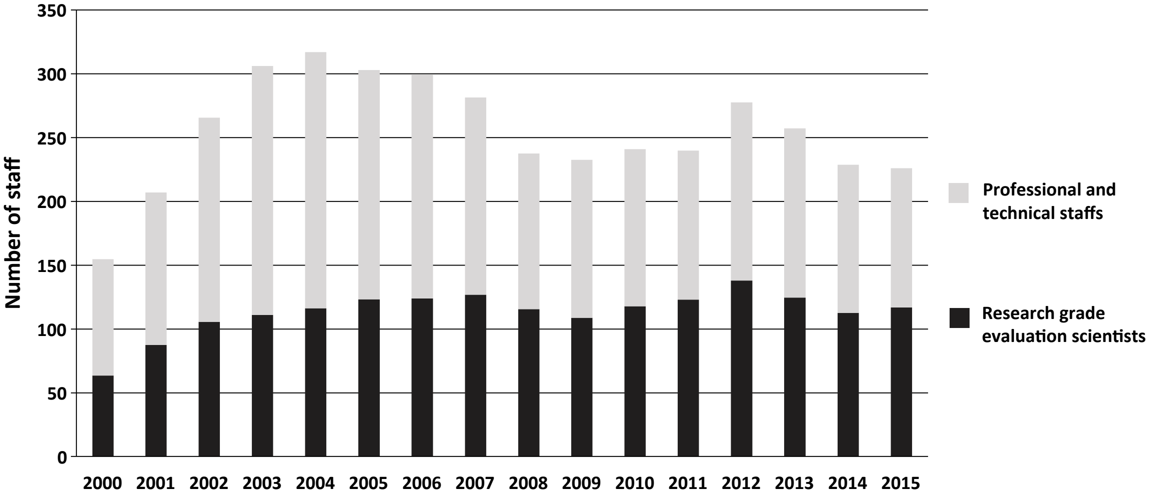
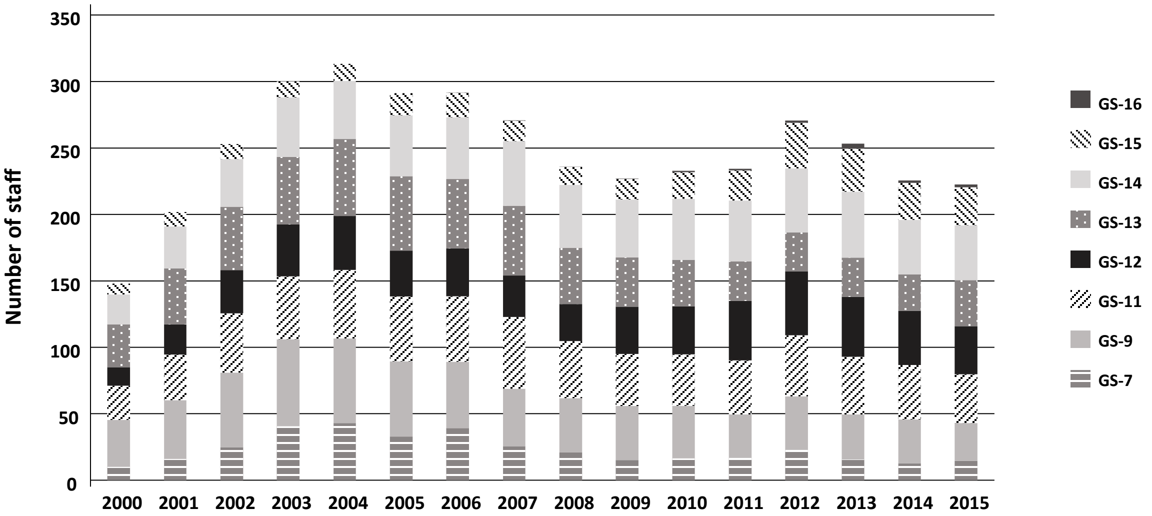


**Figure 3.** Distribution of scientific and technical staff working on the Research and Development Wildland Fire and Fuels program by grade level from 2000 through 2015. The y-axis represents the number of full-time equivalent staff members in each category.



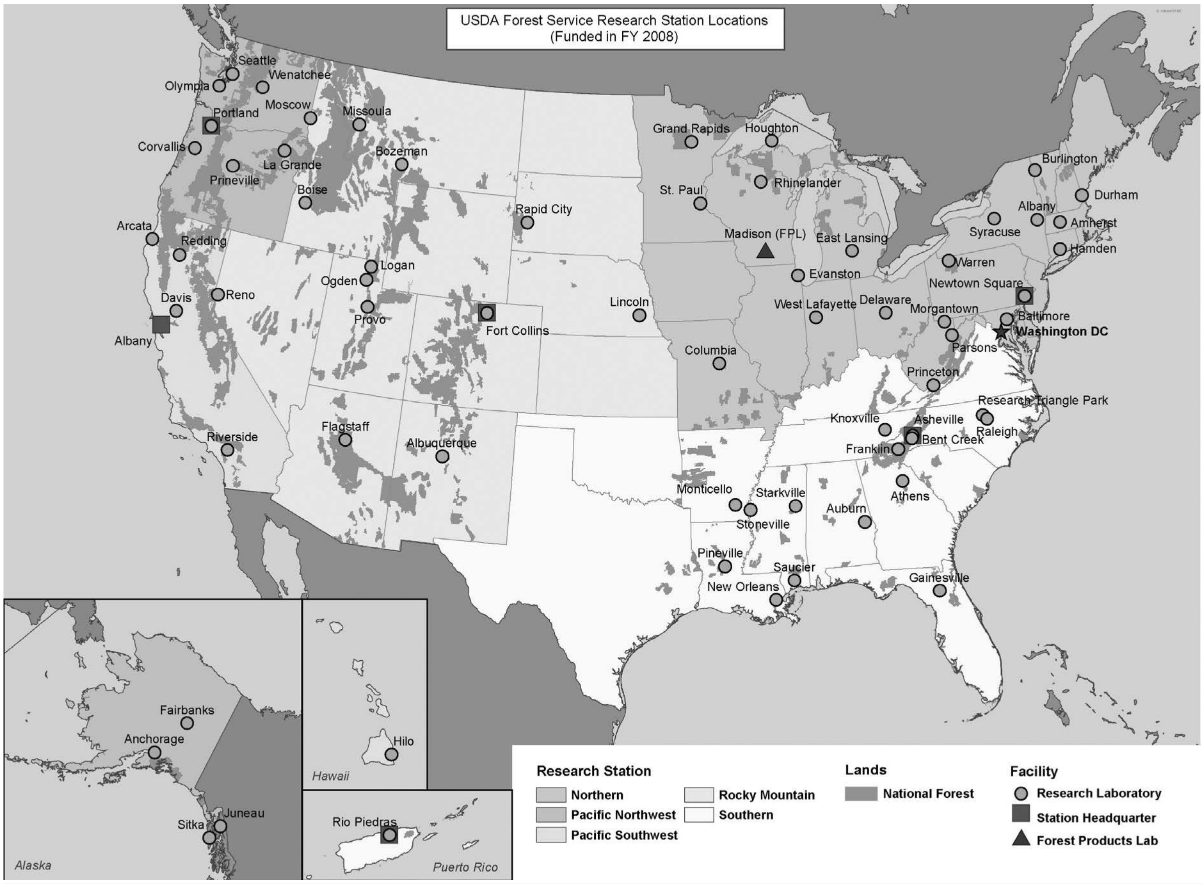
# Facilities

Forest Service R&D scientists conduct research in a variety of settings: in Forest Service laboratories; on Federal, State, and private lands; and in facilities and on lands managed by national and international partners. Examples of unique Forest Service research facilities include the Missoula Fire Sciences Laboratory in Missoula, MT, with its wind tunnels and combustion chambers for experimental fire behavior research; the San Dimas Experimental Forest in southern California, with its long history of postfire erosion and hydrology data and experimental fire research; and the FPL, with specialized facilities for developing, pilot testing, and demonstrating new processes for using small-diameter woody materials. At the Fire Sciences Laboratory in Riverside, CA, an airplane equipped with a newly developed sensor system for monitoring wildfires can be deployed throughout the Western United States to provide high-quality data on active fires for use by incident teams, showing promise for evaluating the performance of fire behavior models.

Our scientists conduct wildland fire and fuels R&D throughout the United States—from Florida to Alaska and from Maine to California, in the tropical forests of Hawaii, and in Puerto Rico—and in many countries around the world, including Australia, Brazil, Canada, Mexico, Russia, and Spain. The research is of varying scales, from local to global, and is conducted in forests, shrublands, and grasslands managed for a variety of purposes, including urban-interface forests, wilderness areas, plantations, utility corridors, watersheds, old-growth forests, wetlands, and aquatic systems.

The Forest Service has an extensive network of 81 experimental forests and ranges (EF&Rs) and more than 480 research natural areas (RNAs), which provide researchers and collaborators with unique long-term data bases and experimental sites (figure 4). These sites, along with the long-term ecological research sites, such as the H.J. Andrews Experimental Forest, represent a wide range of ecosystems, management histories, disturbance patterns, and ecological conditions. EF&Rs and RNAs have associated long-term studies and

**Figure 4.** Boundaries of Forest Service research stations. The Forest Service currently has five research stations; the Forest Products Laboratory (FPL) in Madison, WI; and the International Institute of Tropical Forestry (IITF) in Río Piedras, PR. The Pacific Northwest Research Station (PNW) is headquartered in Portland, OR; the Pacific Southwest Research Station (PSW) is in Albany, CA; the Rocky Mountain Research Station (RMRS) is in Fort Collins, CO; the Southern Research Station (SRS) is in Asheville, NC; and the Northern Research Station (NRS) is in Newtown Square, PA.



monitoring efforts that provide an invaluable record of impacts of and recovery from fire, postfire and fuels treatment, and other disturbances and allow unusual events to be placed in the context of larger spatial and temporal patterns. EF&Rs and RNAs provide opportunities to investigate forest management issues at the appropriate spatial and temporal scales and study the fundamentals of natural ecosystem structure and dynamics. This work has long been recognized as having regional, national, and international importance.

Many of these sites are recognized for their long-term commitment to fire research: Bonanza Creek in Alaska, Blacks Mountain in California, Bent Creek in North Carolina, and the Luquillo in Puerto Rico. For example, the San Dimas Experimental Forest in southern California has been a laboratory for fire research for more than 70 years; research conducted there includes the effects of postfire treatments, fire impacts on birds and small mammals, erosion and hydrology, nutrient cycling and air quality, and long-term hydrologic, vegetation, and weather records. At the Coweeta Hydrological Laboratory in North Carolina, long-term studies are being conducted on the impacts of fire on hydrology and nutrient cycling on vegetation dynamics. The work builds upon and benefits from a more than 70-year record of large-scale vegetation and hydrologic dynamics in southern Appalachian watershed ecosystems. The continued cutting-edge research activities and products from EF&Rs and RNAs are the result of strong partnerships and long-term research efforts with universities, other Federal agencies, tribal governments, State governmental agencies, private industry and private land owners, and international cooperators.

Research on wildland fire and fuels is complex, multidisciplinary, and often requires a long-term commitment. Teams need to be assembled at all levels, from local to international. The Forest Service has the unique ability to provide both expertise and a land base for integrated research at various spatial and temporal scales. Forest Service researchers have a mandate to serve the land and people of the United States; thus, our research is directly tied to the management of public and private lands. Access to forests, rangelands, and watersheds; decades of baseline data; qualified research staff; and broad regional, national, and international networks of cooperators provide a unique resource.

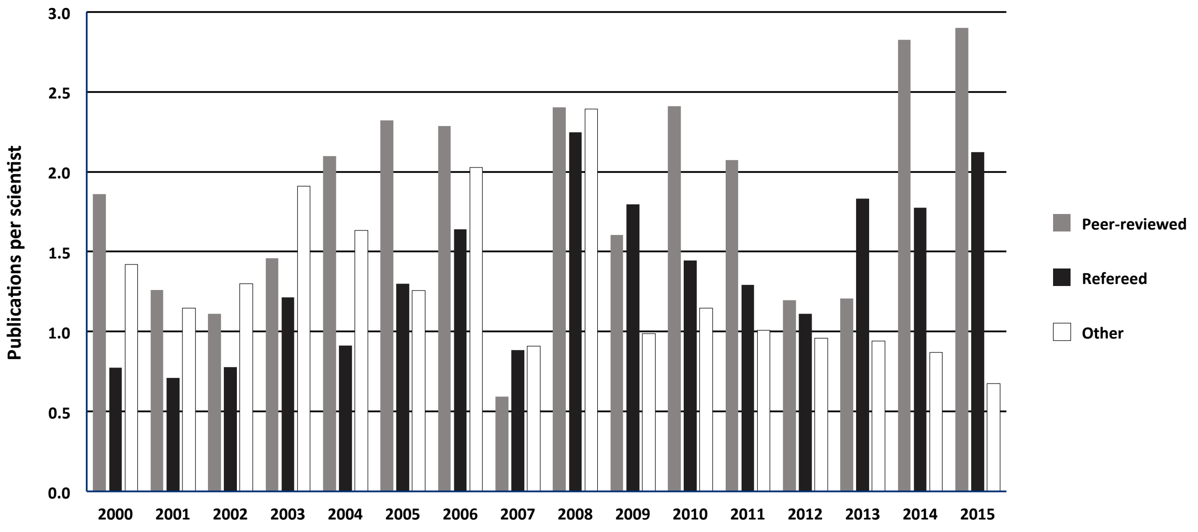
## Publications

In response to increases in wildland fire R&D activity, starting with the initiation of JFSP in 1998 and continuing in 2001 with the start of NFP R&D funding, the number of refereed, peer-reviewed, and popular or user-oriented publications has steadily increased, from 118 publications per year in 2000 to 339 in 2015. From 2000 through 2015, Forest Service researchers reported 8,096 R&D Wildland Fire and Fuels program publications: 3,257 peer-reviewed, 2,521 refereed, and 2,318 other publications, tools, and Web-based products.

This increase in the total number of publication products reflects an increase in all types of scientific publications, from refereed journal publications to publications more aimed at synthesis and science application (figure 5). This diversity reflects the recognition that a solid foundation of high-quality peer-reviewed science is required to support management decisions and the importance of the need to present the results of our science in forms that are useful to our users in the management and policy communities.

The number of refereed publications more than tripled from 2000 to 2015; the number of peer-reviewed publications increased more than 100 percent, and the number of other publications remained steady. The latter is in part a reflection of the increased numbers of tools and products that have been made available to users over the Internet. Not only has the overall number of publications increased since 2000, but the productivity of our wildland fire and fuels scientists appears to be increasing substantially as well. In 2000, the scientists working on wildland fire and fuels R&D produced an average of 4.0 publications per scientist year (SY); nearly 80 percent of these were peer-reviewed or refereed publications (figure 5). By 2015, the number had increased to about 5.6 publications per SY, with nearly 90 percent in peer-reviewed or refereed publications. The data show a dip in productivity in 2007; this may be due to a decrease in funding that year.

**Figure 5.** Trends in refereed and peer-reviewed publications per scientist year from 2000 through 2015.



## Working With Partners

Partnerships in wildland fire and fuels R&D take many forms, from on-the-ground collaboration on individual projects to participation in policy development on national and international levels. Scientists often partner with colleagues in other organizations to accomplish key objectives. Approximately 10 to 12 percent of Forest Service fire research dollars currently are contracted out through grants and agreements. For the R&D Wildland Fire and Fuels program, the outgoing funds average about 25 percent of program funds, with a wide range from station to station. The types of agreements also vary considerably among stations. In some areas of wildland fire R&D, such as developing user interfaces for models, much of the work is done by contract or other types of agreements. Because of uncertainties in funding and a lack of the necessary skills within the current organization, contracting or making agreements is often a more effective solution to getting certain types of work accomplished than hiring new employees. When research groups use cooperators to accomplish major parts of a work program, matching fund requirements with these partners can leverage limited Forest Service dollars to conduct priority research.

Whether through direct funding or other types of collaborations, Forest Service researchers work with a wide range of colleagues and partners around the world. Forest Service research stations reported current collaborations with more than 555 different organizations in their wildland fire and fuels R&D activities between 2008 and 2015. Collaborators include more than 160 universities or academic institutions from nearly every State and a dozen foreign countries, including Australia, Brazil, Canada, China, France, Italy, Mexico, Portugal, and Russia. Federal agency collaborators outside the Forest Service and DOI include the U.S. Department of Defense, U.S. Department of Energy, EPA, NASA, National Oceanic and Atmospheric Administration (NOAA), National Institute of Standards and Technology, U.S. Agency for International Development, and nearly 50 national parks and forests. Forest Service researchers collaborate with a broad range of more than 80 State and local environmental, resource, and planning agencies from Alaska to Florida. Stations also reported nearly 70 nongovernmental organization collaborators, including The Nature Conservancy, The Wilderness Society, Nature Serve, and the National Council for Science and the Environment. Industry partners include lumber and paper companies, and power companies. Many of these various collaborators provide funding or in-kind support for our wildland fire and fuels R&D activities (as discussed in the section on funding). All of them are an essential part of our programs and partners in our success.

In addition to participating in these many direct R&D collaborations, Forest Service R&D headquarters staff, station leadership, and scientists participate in a wide array of interagency and international activities involving information exchange, development of priorities, program planning, and other activities. At a national level, Forest Service R&D fire researchers and research managers are involved in a number of intra-agency and interagency teams, such as the National Wildland Fire Coordinating Group (http://www.nwcg.gov/) and its subsidiary working groups; the Joint Action Group, led by the Forest Service and NOAA, that is developing national priorities for fire meteorology and smoke research; and the air quality and fire working groups of the North American Forestry Commission.

Participation of Forest Service R&D in leadership of JFSP is also a critical mechanism for interagency collaboration in setting research priorities and supporting R&D activities that meet those priorities. The JFSP governing board includes representatives from R&D, fire, and land management from the Forest Service, and five DOI agencies, ensuring broad collaboration and coordination of activities. Priorities set by this interagency group reflect the priorities of the partner management and research agencies for fire R&D within the scope of congressional program direction.

Forest Service Washington Office R&D wildland fire and fuels staff also participate actively in interagency working groups and committees under the Committee on Environment and Natural Resources, which recommends interagency science and technology needs and priorities to the White House Offices of Science and Technology Programs and of Management and Budget. These teams include the Subcommittee on Disaster Reduction, the Air Quality Subcommittee, and the Ecosystems Interagency Working Group of the Climate Change Science Program. All of these activities foster interagency collaboration at the national level and support the development of interagency, integrated R&D priorities.

Participation by Forest Service researchers and national staff in organizations, such as the International Union of Forest Research Organizations and the Global Observation of Forest Cover/Global Office of Land Cover Dynamics Program, fosters international communication and helps ensure coordination of our efforts with other fire R&D activities around the world.