Joint Fire Science Program Smoke Science Plan Conclusion:

Smoke Science Accomplishments Under the Plan

Final Report

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JFSP Smoke Science Plan Final Report Executive Summary

Background: The Smoke Science Plan (SSP) was the guidance and organizational tool of the Joint Fire Science Program for smoke research from 2011 until 2016. It helped to guide the funding and management of 41 research and development projects under four thematic areas. Since its inception in 2011, 29 smoke science projects have been funded. An additional 12 legacy projects, addressing research needs identified in the SSP, were added to the portfolio for a total of 41 projects considered as part of the SSP.

Theme I Smoke Emissions Inventory: Research under this theme was purposed to address the science needed to support an accurate national wildland fire emissions inventory system, improve emission factors, and apply improved emissions inventory tools to evaluate fire's contributions to regional ozone and particulate matter (PM) loadings.

Research compared the effectiveness of top down (e.g., satellite remote sensing) and bottom up (e.g., accounting practices) tools for constructing inventories. Results suggested that fuel loading and fuel consumption were large sources of uncertainty in any large-scale inventory (project 12-1-7-01) confirming earlier modeling comparisons in Theme II (project 08-1-6-10). Methods to improve fuel loading estimates have been identified and an ongoing research project is addressing improving fuel mapping and evaluating its spatial representativeness (project 15-1-01-1). Consumption, another component of emission inventories, was addressed in a Theme II project (08-1-6-10). Model results compared well with field measurements; however, separating flaming from smoldering and treating different fuel strata remain as issues that contribute to uncertainty.

Both laboratory and field studies measured emission factors for prescribed fire and peat fuels (projects 09-1- 3-01, 11-1-5-12 and 11-1-5-16). The complex nature of carbon emissions, especially their volatility and role in generating secondary organic aerosols were studied in depth (projects 09-1-3-01, 14-1-03-26, 14-1-03-44). New understandings have led to new chemical mechanisms for modeling smoke impacts on ambient air quality. These are being used to improve air quality models in a few ongoing research projects (12-1-8-31 and 14-1-03-44

Projects evaluated the relative contributions of fire smoke to both ozone and $PM_{2.5}$ in the US producing a relative ranking of counties where fire is most likely to contribute to national ambient air quality standard exceedances (projects 11-1-6-06 and 12-1-8-31). Tools developed in this research are currently being used at state and local levels to help in the air quality planning process and in retrospective analysis of Exceptional Events.

***Theme II Fire and Smoke Model Validation*:** Research under this theme identified the scientific scope, techniques, and partnerships needed to objectively validate smoke and fire models using field data.

Smoke models generally are hindered by the lack of accurate fuel loading data, especially data that represents the three-dimensional distribution of fuel loading across the fire area (projects 08-1-6-01, 09-1-4-01). Additionally, plume rise is often over-predicted by commonly used simple techniques, which miss the influence of multiple plume cores, and result in significant errors in predicting smoke transport (projects 08-1-6-04, 09-1-4-01). JFSP-sponsored research has verified that the more models are tested in the field or are run through post-fire scenarios, the clearer it becomes that a key need is more and better data sets to evaluate them (project 08-1-6-10, Smoke and Emissions Model Intercomparison Project - SEMIP). Fire and smoke model evaluation and validation require multiple scientific disciplines and data sets that cross those disciplines. It has become clear that to improve fire behavior models, which are an essential component of smoke modeling, work must move to experimental fires of larger size, higher fuel loadings, and elevated burn intensities from previous efforts (project 11-2-1-11, Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment - RxCADRE). It is also clear that for smoke modeling itself such field work must also move into complex fuels with greater fuel loading (than the grasslands previously studied) and higher intensity fires (project 13-S-01-01). An interagency study plan is nearing completion that will identify approaches to gather data needed to validate smoke models (project 15-S-01-01, Fire and Smoke Model Evaluation Experiment - FASMEE).

Superfog, a condition where smoke and fog mix to reduces visibility enough to cause safety hazards, was researched and advances made at understanding the atmospheric conditions necessary for such events to occur (project 09-1-4-05). This work was complemented by work on low intensity and sub-canopy smoke transport (projects 09-1-4-01 and 09-1-4-02). In these studies, and others (notably project 12-3-1-06), the need for gridded weather data at high terrain resolutions was necessary to properly simulate combustion, emissions, atmosphere/smoke interactions, and smoke dispersion.

Theme III Smoke and Populations*:* Research under this theme was purposed to quantify the impact of wildland fire smoke on population centers and on fire workers, as well as to elucidate the mechanisms of public smoke acceptance in light of the needed balance between human smoke exposure risk and ecosystem health risk. Ultimately, this research was envisioned to help in the development of a national smoke hazard warning system/methodology based on best science.

In recent years it has become clear that smoke from fires, especially from “megafires,” can impact not only the wildland urban interface but also large urban areas some distance removed from the fire itself (projects 11-1-7-02 and 11-1-7-04). With more people exposed to wildland fire smoke comes the need to better understand how smoke affects human health, the levels of smoke that create different public health concerns, and how to best warn the public when smoke events are imminent. Also, as fires become more frequent and larger, and the demands on firefighting resources increase, the need arises to understand the effects of extended exposure on firefighter health.

The first major objective of the theme was to address the health impacts of wildland fire smoke on fire workers and the public. Four projects were funded and all are ongoing, but two projects have significant preliminary findings. Project 14-1-04-16 is investigating the toxicity of smoke emissions, marking the first time that the cardiopulmonary toxicity and mutagenicity of emissions from wildland fuels have been studied. Fuel types and combustion phases were found to dramatically alter the emission characteristics, mutagenicity, and lung toxicity of wildland fire smoke. The findings have prompted the Environmental Protection

Agency (EPA) to undertake further research into the effects of fire emissions on pulmonary function and toxicity, neurobehavioral changes, and cardiovascular function and toxicity from acute and sub-chronic inhalation exposure of smoke. The EPA also is interested in investigating the effects of aged wildland smoke mixed with urban air pollution. Project 14-1-04-9 is characterizing the health and economic burden of wildland fire smoke, representing the first attempt to quantify this across the continental US over multiple years. Work is showing that although effects differ from year to year, wildland fires pose a significant burden to public health on an annual basis. Populations in California, Idaho, Oregon, Louisiana, and Georgia are most affected. Project 14-1-04-5 is working to develop models to identify vulnerable populations that can assist public health agencies in targeting messages and interventions during wildland fire events. Project 13-1-02-14 is developing a set of risk-based exposure criteria for wildland fire fighters, which could be included in future drafts of NWCG's *Wildland Fire Personnel Smoke Exposure Guidebook.*

The second objective focused on the public's perception and tolerance for smoke. The three projects funded by JFSP represent the only existing social science research on wildland fire smoke for the US. Findings confirmed that effectiveness of public smoke messaging is increased when the background of the audience, including the types of vegetation types they are familiar with and past experience with fire, is aligned with communication goals (project 10-1-3-02). The two strongest predictors of public tolerance for smoke from wildland fires are being aware of prescribed fire's benefits and trust in public fire managers (projects 10-1-3-07, 12-3-01-21). These findings will help frame wildland fire smoke messages to the public.

The third objective of this theme was to determine how to use information on health effects and public perceptions of risk to develop public health smoke messages during large fire events. To determine the best means of communicating smoke hazards to the public, JFSP funded three projects that are actively working together to develop an operational smoke hazard warning system (projects 13-C-01-01, 14-1-04-5, 15-1-02-4). In addition to advances in aggregating and distilling many complex datasets related to fire, smoke, and air quality into a central repository necessary for predicting smoke events and developing a smartphone application that include a visual range assessment tool, these projects have created a broad collaboration with the National Weather Service, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, EPA, Center for Disease Control and Prevention, and others to guide messaging and products and to create a collective vision for moving forward. The initial operational outlet of the Smoke Hazard Warning System is EPA's existing website, *AirNow*.

Theme IV Climate Change and Smoke: Research under this theme was purposed to better understand implications of climate change on wildland fire smoke and of wildland fire smoke on climate change using United Nations Intergovernmental Panel on Climate Change (IPCC) 2013 emissions scenarios for guidance. Research under this theme addressed black carbon generated from fire smoke, potential impacts from megafires on large urban areas, and simulation of future smoke impacts in under future potential climates.

Research was funded to quantify potential contributions of fire smoke to ambient black carbon concentration and deposition in the Artic and other regions (projects 10-S-2-01 and 11-1-5-13). Results have quantified: 1) fire emission's contributions to the black and brown carbon components of PM and 2) source regions and meteorological situations leading to black carbon deposition. One these modeling studies simulated potential black carbon deposition patterns in the northwestern United States (project 11-1-5-13), while the other developed an on-line tool for assessing potential for wildland fire black carbon artic transport.

Future megafires and their potential impacts, especially on urban areas, were estimated in two projects (projects 11-1-7-02 and 11-1-7-04). A special study paper addressed the state of science in coupled climate change, ecosystem, fire and smoke simulation modeling and suggested preferred approaches to working with the complex chain of interacting models. A second special study paper summarized the contemporary understanding of future fire and smoke on the climate system. Finally, two continuing studies are considering the impact of IPCC emissions-dependent climate projections on smoke and air quality in the U.S. and specifically in the southeastern U.S. through the mid-21st century (projects 13-1-01-4 and 13-1-01-16).

Remaining Challenges as Seen by the JFSP Smoke Science Advisors After Consideration of the Research Accomplished Under the SSP

A key smoke chemistry question remains about just how much understanding of this complexity is necessary for smoke management purposes. The absence of a nationally implemented fire inventory methodology, applied across all ownerships and fire types (wildfire, prescribed fire, agricultural burning), means smoke emission inventories are likely to continue to be inconsistent, uncertain, and potentially biased. Most projections for the western U.S., regardless of the specific emission scenario chosen, suggest a warmer drier climate with more extreme weather events so that fuel loadings and future fire occurrence become harder to estimate. Projections for other regions of the US are less clear. Because both fire and the smoke it generates occur, by and large, at local scales, whereas climate change analysis tools are most valid at global scales, differences in spatial scale and the associated controlling processes must be bridged for before these studies can be considered to be particularly useful for future planning.

As climate and demographics shift in the USA, health impacts from smoke will become of greater concern, especially understanding effects of mixes of smoke and urban pollution. As megafires increase, smoke transport into large urban centers will increase, changing needs for public warnings and education. And the long-term impacts on fire workers need to be studied, if not by JFSP, then by programs dedicated to this task. Increased use of models for developing information for health and safety alerts will necessitate improving models; such improvements must come from field data and theoretical work (see FASMEE). Smoke plume rise, secondary organic aerosols, how differing vegetation complexes and even phenologic stages of plant growth affect emissions, atmospheric chemistry changes during long-range transport—all of these issues will need further consideration and research.

Prescribed fire will come under more scrutiny and perhaps even subject to air quality restrictions in areas of the country designated as “non-attainment” for ambient standards for ozone and particulate. Such restrictions, however, may be a lesser worry if wildfire smoke emissions become “politicized” due to health impacts to urban populations. Both fire behavior and smoke models suffer from 1) a lack of computing power to run models with physics that are close to simulating reality and 2) a fundamental need for better understanding of the processes involved and the scientific talent needed to resolve these processes into mathematical formulae. Although a need exists to validate and test smoke mitigation practices in the field, such work may be overwhelmed by the rapid change in fire ecology resulting from a warming climate and catastrophic weather events.

Finally, it must be recognized that climate-driven processes are stochastic and non-stationary meaning they will always remain, to a certain degree, unpredictable. The past is not a good predictor of future events, especially regarding extreme weather behavior. Thus smoke impacts from future fires in a changing climate will remain highly uncertain. JFSP supported research has served to illustrate the breadth of potential for future smoke impacts. Continued research by the climate change and fire science communities will lead toward more useful, emissions-based regional climate and associated ecosystem projections. As these improvements develop JFSP may wish to consider further investment in the fire and smoke consequences of climate change.

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Joint Fire Science Program Smoke Science Plan Conclusion: Smoke Line of Work Accomplishments Under the Plan

INTRODUCTION

The Joint Fire Science Program Smoke Science Plan (JFSP/SSP) which began in 2011 was the guiding document that informed research funded under four thematic areas; 1) Smoke Emissions Inventory Research, 2) Smoke Model Validation Research, 3) Smoke and Populations Research, and 4) Climate Change and Smoke Research. The objective of the plan was **to move smoke science knowledge forward incrementally over a five-year funding period, to meet a specific set of science needs identified by managers and scientists.** Since its inception in 2011, 29 smoke science projects have been funded. An additional 12 legacy projects, addressing research needs identified in the SSP, were added to the portfolio for a total of 41 projects considered as part of SSP. As of April 2017, 25 of these are completed. Currently 16 projects remain active with all results due in 2018 when all SSP funded research is to conclude. Completed and still active projects have addressed: A) weaknesses in existing smoke emissions calculations and providing science to improve them; B) strengths and weaknesses in existing smoke and air quality models and modeling systems and how they might be validated through field and laboratory measurements, C) tools to assess smoke's contribution to air quality related health concerns both for fire-line personnel and the general public, and D) how generally accepted scenarios for climate change may change fire regimes and resulting smoke emissions in the next decades. Under the SSP major new insights have been gained into visibility and smoke concentrations for health hazard warnings, weaknesses in current emissions inventory techniques, understanding the errors and strengths of current smoke models, how smoke is potentially adding to ozone and PM2.5 concentrations, and fundamental advances in how to project smoke impacts under climate change. The SSP has also objectively increased the amount and significance of interagency cooperation in JFSP funded smoke research, developing for example, a major new multi-agency national initiative on field studies for smoke model evaluation. Final outcome of this plan's research, organized by each of the four themes, will be further discussed in theme focused sections demonstrating how the SSP research will have a lasting significant impact on how fire, especially prescribed fire, will be treated in future US air quality regulatory actions, smoke/air quality model development, smoke public health strategies, and fire management under a changing climate. In this report we will discuss how the SSP as an activity has resulted in better, more user-focused smoke research for the Joint Fire Science Program and how the SSP science legacy may be best leveraged for the future.

JFSP Lines of Work and Smoke Science

The Joint Fire Science Program has, since its inception in 1997, sponsored a broad spectrum of fire science. In 2005, the JFSP began to include thematic areas of a complex and enduring nature in its science portfolio, which were designated 'lines of work.' As stated in the JFSP Science Delivery Strategy (Barbour, 2007), *"Lines of work address* *complex management problems and require a coordinated multi-year approach to develop integrated solutions useful to fire and fuel managers. Lines of work are intended to guide JFSP investments over a period of 3-5 or more years."* This conceptualization allowed JFSP to organize in a strategic manner both its smoke science endeavors and its funding of discrete projects. Smoke and emissions science lends itself well to strategic planning, as we will show in the following sections.

Smoke from wildland fire is an air contaminate that is indirectly managed by non-fire agencies under the authority of the Clean Air Act. By 'indirectly managed' we mean that wildland fire is neither a stationary source nor a mobile source of air pollution and it is not specifically addressed under the regulatory programs set by the Act for each of these. Fire, rather, is a source whose emissions intermittently contribute significantly to the air quality in an airshed. These emissions are not as manageable as conventional air pollution sources using classical methods of emissions reduction. The fact that wildland fire contribution to air contamination is both complex and variable has led to confusion, controversy, and sometimes distrust between land and air resource managers. This is especially true concerning regional haze and national ambient air quality standards (Sandberg et al., 2002). One debated topic is whether or not prescribed fire can be seen as purely a public good, and smoke produced from prescribed is at worst a necessary temporary impact that must be accepted for a greater benefit (Bushfire Front, 2008). Another topic debated is whether smoke can be managed at all, the argument being that since wildfires by definition can't be 'managed' people must just accept that worse wildfire smoke episodes will unavoidably occur unless small, better timed, smoke events occur under prescribed fire. In this mix there is also the reality of a potentially warming climate, exacerbating potential fire impacts (McKenzie et al., 2014). One does not have to be involved in such debates for long before it becomes clear that much of the problem stems from misinformation, especially about technical aspects of both fire management and air quality management. It has consequently been clear to JFSP that smoke research is an important part of its overall fire research mission. But questions remain about the scope, detail and mechanics of how to conduct smoke research in an organized objective productive line of work.

Developing the Smoke Science Plan

As part of the line of work concept, in 2007 JFSP commissioned two smoke roundtables (meetings of experts and scientists) to develop lists of smoke research needs with one to represent the eastern and one to represent the western parts of the country (SRA International Inc., 2007). A science review of the roundtables revealed both strengths and weaknesses in the information gained at these roundtables (Potter, 2011). Although the roundtables had some outstanding features, they lacked vetting and were considered somewhat limited in scope. In 2010, Nine Points South Technical Pty Ltd was contracted to develop a plan to guide JFSP smoke science for a 5-year period. Using the results of the roundtables and both face-to-face interviews and on-line questionnaires (Riebau & Fox, 2010), a new Smoke Science Plan (SSP) was developed (JFSP, 2010). The objective here is to describe how the plan was developed. By developing a plan, we mean both the written guidance of a plan as well as creating methodology and culture to enable a realized result.

After the plan was written, reviewed, and accepted by the JFSP much work remained to develop the plan into a line of work. Although the plan included guidance as to how it might be implemented (e.g., research topics to be pursued for each year for a five-year period), this was far from a pattern of action that would create a cogent line of work. To accomplish this a 'social framework' was needed. This framework would need to link JFSP Project Management, the JFSP Board of Directors, JFSP current and perspective smoke scientists, advisory groups such as the NWCG Smoke Committee (SmoC), fire managers, and air quality managers in order to create a common understanding and work toward a consensus on how to focus JFSP smoke research for the next five-year period. As part of this unique plan development, JFSP contracted the authors of the plan to act as an advisory team charged with finding the balance between keeping the line of work on track while allowing necessary and appropriate flexibility. It would be hubris to claim such a balance was accomplished completely, but it would also be untrue that this was not at the core of the SSP development. In short, the written document of the SSP was a touchstone but the real development of the SSP was a process that evolved and developed over time, under the JFSP 'lines of work' guideline. The challenge was to coordinate a steadily evolving knowledge base with oversight and focused direction from the JFSP's Board of Directors with the formally adopted SSP. Among the parties listed above consensus was not an objective. The objective was to develop a creative balance of partnership (some long-term while others more ephemeral) based around simply stated, achievable goals under four thematic areas of wildland fire smoke research. Thus the development of the SSP and the smoke line of work were not the creation of a document, but rather the development of a managed process.

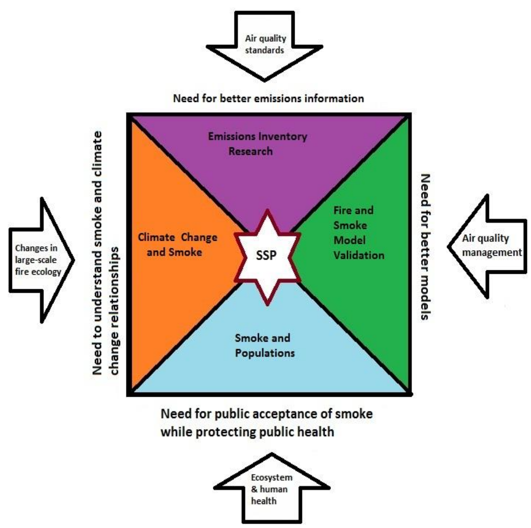

*Figure 1: **The Smoke Science Plan (SSP) unites four themes, each of them addressing a need, and each need resulting from a large 'driver' that has historically impacted and will continue to impact wildland fire management in the United States.***

Implementing the Smoke Science Plan

The SSP was implemented through a process of proposing research objectives, reviewing and clarifying them with both JFSP leadership and the JFSP Board then formulating and requesting focused research proposals designed to incrementally advance knowledge towards achievement of the objectives of the four plan themes. The SSP themes and their objectives are:

- The objective of the *Smoke Emissions Inventory Research Theme* is to develop science and knowledge needed to improve national wildland fire emissions inventories, paving the way for the design of a national consensus inventory system.
- The objective of the *Fire and Smoke Model Validation Theme* is to identify the scientific scope, techniques and partnerships needed to objectively validate smoke and fire models using field data.
- The objectives of the *Populations and Smoke Theme* are to quantify the impact of wildland fire smoke on population centers and on fire fighters, and to elucidate the mechanisms of public smoke acceptance in light of the needed balance between human smoke exposure risk and ecosystem health risk. Ultimately this is envisioned to help in the development of a national smoke hazard warning system/methodology based on best science.
- The objectives of the *Smoke and Climate Change Theme* are to better understand implications of climate change on wildland fire smoke and of wildland fire smoke on climate change using UN IPCC future climate scenarios for guidance (IPCC, 2013).

SMOKE SCIENCE PLAN
"SOCIAL FRAMEWORK"

The JFSP Smoke Line of Work 'social framework', we define here, as the community of interest that participated in the implementation of the SPP that included JFSP management and smoke researchers, fire management, and air quality interests. Each year research topics were brought to the JFSP Governing Board and explained within the context of the plan and the line of work.

As mentioned the SSP plotted a course toward achievable goals that had been distilled from management needs, into a series of incremental research topics (see Appendix B Smoke Science Plan Milestone Tracker). The proposed topics were designed to achieve a step-wise progression of new science based insights on smoke with the progression broken down into yearly topics that could be advertised as requests for proposals. In this manner it was indeed possible to set goals for a relatively short period of time (in this case five years) and define knowledge needs or 'gaps' to achieve such goals. The SSP process was simply 1) keeping JFSP smoke science knowledge goals within the scope of its mission, 2) reasoning the incremental knowledge advances needed to achieve such goals, 3) placing these needs in order, and 4) then timing the activities for addressing the knowledge needs over the five-year period.

Once this was understood, generally agreed, and consensus reached within the SSP 'social framework' the incremental progress of smoke research could begin. The JFSP Smoke Line of Work 'social framework', we define here, as the community of interest that participated in the implementation of the SPP that included JFSP management and smoke researchers, fire management, and air quality interests. Each year research topics were brought to the JFSP Governing Board and explained within the context of the plan and the line of work. After their suggestions and approvals were incorporated, these were preliminarily brought into wider discussion with the other parties in the 'social framework' and if not vetted, at least they received acknowledgement. Keep in mind that the entire SSP five-year smoke research topics list was available to anyone in this 'social framework' and the general public by accessing the plan that was available on-line. Uniquely, potential research funding topics were available for scientists to view years before the annual 'social framework' process began. After this initial 'vetting' of the topics, formal research proposals were sought and reviewed. This review of proposals also took a unique course. Scientists and managers, and sometimes the advisory team, together reviewed proposals, with the JFSP Governing Board receiving written comments from both the panel reviews and the SSP advisors. In the end, the JFSP Governing Board made all decisions on what would and would not be funded.

SSP Communications

The Communications Plan for SSP, originally conceived by Tim Swedberg of JFSP, focused on strategies to build awareness of the Smoke Line of Work and then provide forums for more in-depth understanding of the individual project results. Key to this process was the development of brief summary statements for each research project by the smoke science advisor team (Nine Points South). The Summary Statement for each project would answer the questions *why is the work important, what are the key findings,* and *what are the management implications*? These 1-2 page summaries were used to design announcements for informational webinars, communicate key points to the JFSP Board members, and provide a quick overview of project results potentially for use by the Fire Science Exchange Network (https://www.firescience.gov/JFSP_exchanges.cfm). Summary Statements have been written for all completed projects, and for active projects that provided preliminary findings, and have been compiled into an updated booklet for JFSP.

Articles in publications focused toward fire and smoke managers were used to build awareness of the Smoke Line of Work (LeQuire & Hunter, 2012; Riebau & Fox, 2010). Updates on the process and results of SSP research have been published in IAWF's journal, *Wildfire* (Fox, 2016), and an article has been accepted for publication in *Fire Management Today* (Riebau et al., in press).

The IAWF International Smoke Symposia (2013 and 2016) and Fuels and Fire Behavior Symposia (2013 and 2016) provided excellent venues to showcase JFSP projects and to build and strengthen collaborative partnerships between diverse groups with a mutual interest in wildland fire, smoke and air quality. Nine Points South actively participated in all four symposia; designing workshops to highlight research results and providing updates on SSP progress in both special and plenary sessions.

Several key audiences were kept aware of smoke science research results throughout the life of the SSP. The National Wildfire Coordinating Group Smoke Committee (SmoC) represents key user groups (fire and smoke managers, and air regulators, and air quality and smoke scientists) and they were the primary targets for a series of online webinars that allowed investigators (PI) the opportunity to share results. As projects were completed, PIs were requested to present a one-hour summary of their work in webinar format. The smoke science advisors worked with the PIs, JFSP and SmoC to schedule and announce these webinars. A total of 12 webinars were produced and recorded, and are available through the Wildland Fire Lessons Learned Center (http://www.wildfirelessons.net/resources/advancesinfirepractice/webinars).

Workshops were another venue for sharing the smoke science funded by JFSP. Nine Points South held a workshop in 2013 (with on-site and remote participation opportunities) that allowed PIs to share findings with JFSP and each other. This webinar had the unexpected consequence of generating additional collaboration between projects. Additionally, smoke science advisors participated in meetings of the Fire Science Exchange Network and discussed possibilities for collaboration to disseminate research findings.

Major Accomplishments

How then, does an extramural research organization such as the JFSP assess that its goals for the smoke science are met? Review of progress is difficult in an area of science where a specialized knowledge base is required yet has implications to multiple specialized management areas (e.g., air quality, fuels management, smoke management, public health management, public messaging/communications). In a research organization, whose mission is to bridge fundamental research and applied research, the members of the JFSP smoke science line of work 'social framework' also act as a body of judges. As the process of adding yearly incremental work (i.e., projects) to the Smoke Science Plan research portfolio progressed, judgments were made within the 'social framework' context to assess overall progress towards theme objectives. Tangible things, such as formal project progress reports and final reports, are certainly products. But harder to gauge is the impact science advances have on the thinking and actions of user of communities. Citations made of papers resulting from sponsored research are certainly one measure. But how can the change in viewpoint of the community by an increase in scientific knowledge be measured? Especially when articles published in journals and other outlets are now often available worldwide on the Internet?

Another significant consideration is that the JFSP mission includes not only the conduct of research on fire and its management but perhaps more importantly to affect improvements in fire management in the US. How is it possible to judge the effectiveness of smoke science research in improving fire management?

One fortunate occurrence during the course of the SSP has been development of the International Association of Wildland Fire (IAWF) International Smoke Symposia. The first symposia had the objective: *" ... to bring together air quality, fire, and smoke specialists from the research community, non-governmental organizations (NGOs), local/state/federal government agencies, tribes, and private practitioners and organizations to discuss the state-of-the-science and state-of-the-applied-science for smoke management and addressing the air quality impacts of wildland fire smoke* (IAWF, 2013*)."* The first meeting held in 2013 saw 103 oral presentations, 8 plenary speakers and 34 poster posters presented with, we estimate, about 49% of these presentations having some intellectual ties to JFSP funded smoke research work. We have made this estimate by comparing our information on authors and presentation information, comparing this to JFSP research projects funded. The symposia did and will allow JFSP smoke science research results to be shared across a broad audience, sharing and putting such results into the context of smoke research world-wide.

The first symposium was so successful that a follow up was conducted in November 2016. At this Symposium (ISS2) there were 139 oral presentations and 17 poster presentations. The SSP was directly responsible for a full day Workshop on "Developing Strategies for Prescribed Fire under new US Ozone and PM Standards and Exceptional Event and Regional Haze Rules using recently developed tools", as well as 5 review presentations on the Program. And again, JFSP funded smoke research was directly or indirectly involved in well over 50% of all the presentations.

JFSP funded research has contributed to the BlueSky modeling system, thorough the Smoke and Emissions Model Intercomparison Project (SEMIP), The NWCG Smoke Management Guide for Prescribed Fire (currently under revision), and others (JFSP, 2008). Additionally, JFSP funded results have made improvements in the EPA's triannual National Emissions Inventory and state smoke management plans. A last example to cite is the development of DEASCO3 and PMDETAIL and their growing potential to influence state strategies for ozone and $PM_{2.5}$ standard implementation plans with regard to smoke. One may argue that these above may be overstatements and exaggerations. But if we keep in mind that progress in on-the-ground operational practice is most always a synergism of many pieces of information and discrete actions of managers added together, we come to a better understanding of the impact of science. Often fundamental science advances are leveraged with the canniness of individuals to make such science insights useful, and a long-term focused research endeavor's true impact becomes one of systemic change to management often brought about by non-researchers in partnership with researchers. We believe that we have witnessed this and feel privileged to have been just a small part of the monumental work of JFSP funded smoke researchers.

This final project report cannot give a complete view of the full extent and impact or the systemic changes we see being engendered by the SSP research, because a significant number of projects have yet to be completed. However, in subsequent chapters each Theme's progress and accomplishments will be described in more detail. Here we provide a synopsis presented with brevity in Table 1.

Table 1: SSP themes, knowledge gaps and gains, and resultant impacts.

Theme Objective	Knowledge gaps	Knowledge gained	Resultant impact	SSP 5 Year Goal Achieved
Theme I: Creating a better knowledge base for an objective national smoke emissions inventory	Strengths and weakness of current inventory methods; uncertainty in emissions factors; lack of information on SOA influences on ambient ozone and PM	Understanding of assumptions used in current inventories and improvements to them; improved science system to calculate fire impacts to ozone and PM; better knowledge of fire SOA emissions	Improvements to EPA National Emissions Inventory regarding fire; planning tool for ozone and PM used by states and FLMs; new SOA science concerning fires in regional modeling	YES (some work still in progress that will close the gap even further)
Theme II: Creating a national scientific imitative to validate smoke models	Lack of experimental design for testing smoke models in real-world conditions; lack of appropriate field data to test models; lack of partnerships and resources for a large smoke model validation campaign	Detailed multi-disciplinary data collection methodology to collect fire and smoke model validation data in 'real world' burns; model validation science community and 'social framework'; Development of a National Smoke Model Validation plan and process (FASMEE)	Large scale field experiment will commence in 2017; Multi-entity science partnerships established; Funding for model validation work realized; science teams for model validation assembled; field locations and burn types determined	YES (FASMEE is now underway)
Theme III: Advancing smoke impacts and public acceptance science to facilitate a national smoke hazard warning system	Lack of data and models on health impacts of smoke to the public and to a lesser-extent, fire workers; lack of knowledge on public acceptance of smoke; lack of understanding how hazard warnings should be best developed and promulgated	New information gained on which factors improve public acceptance; better messaging in smoke described,, and ,better understanding of smoke impacts to fire-worker health;	Information being used to help avoid smoke exposure in fire camps; potential for smoke transport into urban areas from mega-fires being recognized and incorporated into warnings; visual range and smoke concentration warning schema re-evaluated	YES (however, more work on smoke exposure to the public underway; studies of smoke impacts to cell physiology underway)
Theme IV: Advance objective understanding of wildland fire smoke and changing climate	How will climate change alter fire ecology and smoke; how can such projections be approached and developed	Transport of smoke in to large urban areas under mega-fires described and projected. Guidelines on procedures to make sound scientific projections of future fire ecology and smoke; downscaled climate and fire ecology and smoke impact data sets out to 2050	Changes in fire ecology methodology for projections under a changing climate; improved understanding of extreme fire season implications for smoke	Partially (work is still underway and when complete objective will likely be met)

SSP THEME I – EMISSIONS INVENTORY RESEARCH

The objective for the smoke emissions inventory research theme is to develop new science and knowledge that would support and define an accurate national wildland fire emissions inventory system. Emissions inventories are fundamental to air quality management. For smoke, at least two distinct types of emissions inventories are needed. One type is for real time (or as close as possible to real time) emissions used to model smoke concentrations to aid operational decision-making during fire events or during a series of geographically and meteorologically related smoke events. The second type is a retrospective emissions inventory for regulatory purposes, using fire emissions data corrected and quality-assured after the fire has occurred to help quantify fire impacts on the measured air quality during and following fire events. This quantification is needed for both planning of future emissions limitations (State Implementation Plans) and for segregating human from natural contributions (Exceptional Events Policy). Of course, this is a broad simplification but clearly these two inventory categories address different scientific questions and relevant time and spatial scales (Fox & Riebau, 2000; Battye & Battye, 2002). Under the Emissions Inventory theme JFSP research has sought to provide science to clarify and improve both types of inventories. In the original SSP we envisioned the following research topics:

1. Understanding smoke emissions, especially as they contribute to new ozone and PM standards;
2. Emissions factors improvement and development especially for organic aerosols;
3. Precursor emissions for ozone, regional haze and black carbon;
4. Fuel consumption measurement research for emissions calculations;
5. Remote sensing tools for emissions calculation;
6. Fine scale meteorology and turbulence influence on smoke emissions;
7. Plume dynamics and emissions chemistry;
8. National wildland fire smoke emissions inventory proof of concept;
9. Design needs for a national interagency smoke emissions inventory system.

As the SSP draws to a close, we have addressed all these topics either directly or, tangentially. The specific projects that have been funded are presented in Table 2.

Table 2: JFSP projects funded that address emissions inventories. Details of projects including final reports can be accessed through the JFSP website: https://www.firescience.gov/index.cfm

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Smoke Emissions Inventory Theme	Status
Experimental Determination of Secondary Organic Aerosol Production from Biomass Combustion.	Jeff Collett 09-1-3-01	• Found increases of approximately 70% in fine particle mass as smoke plumes "age", which has implications for human health and visibility. • Emissions inventories developed will improve fine particulate modeling. • Models from this project can be used for regional haze planning, and to better understand the contribution of biomass burning to reactive nitrogen deposition in sensitive ecosystems.	Completed
Influence of Fuel Moisture and Density on Black Carbon Formation During Combustion of Boreal Peat Fuels	Brian Benscoter 11-1-5-16	• Remote sensing applications can be used for estimating peat land water table position and surface soil fuel moisture, which can inform fire behavior assessment models. • The threshold of 200% GWC can be used to structure prescribed or wildland fire decisions to minimize the likelihood of burning when direct measurements or indirect indices suggest a high smoldering risk due to low peat fuel moisture content. • Research results expand our capacity to represent and accurately estimate fine particulate emissions during peat land fires for regional or national air quality and emissions inventories.	Completed
Deterministic and Empirical Assessment of Smoke Contribution to Ozone – DEASCO3	Tom Moore 11-1-6-06	• Unique and flexible set of tools created for a web map browsing environment allow managers a variety of spatially oriented ways to interrogate the data bases, ozone monitoring data, fire emissions data and modeling results included in the system. • Complex technical analyses of historic fire events transformed into instructive tables, charts and maps that help describe how and to what extent fires contribute to ambient ozone concentrations. • The DEASCO3 project created a dynamic and accessible web-based tool that allows resource managers to participate more fully in ozone air quality planning efforts with state and federal air regulators.	Completed
Critical Assessment of Wildland Fire Emissions Inventories: Methodology, Uncertainty, Effectiveness	Wei Min Hao 12-1-7-01	• A reference emissions inventory has been developed based on site-specific fire data linked with FIA data and new emission factors. This is being developed as a new Missoula Fire Lab Wildfire Emissions Inventory (MFLEI). • Overall, fuel consumed is the largest source of uncertainty in emission inventories, particularly for forest fires. Deviations of fuel load consumed are often sufficient to outweigh differences in burned area. • Pre-fire surface fuel loadings are inconsistent with Forest Inventory and Analysis (FIA) data. • Improved mapping of fuel loading, especially for forests is needed to reduce the uncertainty of the Wildland Fire Emissions Inventory System (WFEIS) (This is being addressed by JFSP Project 15-1-01-1, French).	Ongoing

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Smoke Emissions Inventory Theme	Status
Assessment of Prescribed Fire Emissions and Inventories	Sim Larkin 12-1-7-02	• *Comprehensive assessment of systems that produce speciated fire emissions information over a range of needs, from detailed inventories for smoke modeling to national annual totals for carbon reporting.* • *Create a Catalogue describing each fire emissions system including its use, capabilities and limitations.* • *Create a comprehensive Technical Repository associated with the Catalogue to document all aspects of each fire emissions system*	Ongoing
Particulate Matter Deterministic and Empirical Tagging and Assessment of Impacts on Levels - PMDETAIL	Tom Moore 12-1-8-31	*Preliminary Findings* • Unique and flexible set of tools created for a web map browsing environment allow managers a variety of spatially oriented ways to interrogate the data bases, fine particulate monitoring data, fire emissions data and modeling results included in the system. • Complex technical analyses of historic fire events transformed into instructive tables, charts and maps that help describe how and to what extent fires contribute to ambient fine particulate concentrations. • The PMDETAIL project is creating a dynamic and accessible web-based tool that allows resource managers to participate more fully in fine particulate air quality planning efforts with state and federal air regulators. The tool also enables comparative analyses for fire's contribution to visibility impairment and the occurrence of Exceptional Events that influence national ambient air quality standard (NAAQS) determinations.	Ongoing
Phase Dynamics of Wildland Fire Smoke Emissions and their Secondary Organic Aerosols	Sonia Kreidenweis 14-1-03-26	*Preliminary Findings* • *Modeling studies found that ~35% of total aerosol mass lost during a typical experiment could be attributed to organic vapors absorbed into Teflon walls of the test chamber.* • *Aerosol evolution in biomass-burning plumes is largely dependent on the nature of the fire and on the ambient conditions (i.e., key parameters are fire size, emission mass flux, and atmospheric stability).* • *Results of observationally-guided modeling studies suggest that the contribution of secondary organic aerosol may be underestimated by currently-recommended aerosol yields. However, in the atmosphere, much of this secondary organic aerosol may be compensating for evaporation of primary organic aerosol, and thus the effects on net aerosol mass from biomass burning activity may be small, although the composition of primary and secondary aerosol is different and should be accounted for in studies of air quality and health impacts.*	Ongoing

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Smoke Emissions Inventory Theme	Status
Synthesis of Comprehensive Emissions Measurements and Multi-scale Modeling for Understanding Secondary Organic Aerosol Chemistry in Wildland Fire Smoke Plumes	Kelley Barsanti 14-1-03-44	*Preliminary Findings* • *Created the most comprehensive non-methane organic compound (NMOC) emission factor database to date by compiling data from multiple advanced, analytical approaches.* • *Identified a large number of compounds that are likely SOA precursors and currently not represented in emissions inventories.* • *Determined that some NMOCs (including SOA precursors) likely are partitioned between the gas and particle phases, and thus their gas-phase emission factors will vary with particle loading.* • *In box models, predicted gas- and particle-phase pollutants and precursors are very sensitive to changes in the emissions inventories and subsequent changes in surrogate species profiles.* • *In comprehensive air quality simulation models, ozone and SOA formation are also somewhat sensitive to changes in emissions inventories; in some cases, maximum predicted SOA concentrations doubled.*	Ongoing
Mapping Fuels for Regional Smoke Management and Emissions Inventories	Nancy French 15-1-01-1	*Preliminary Findings* • *Completed the compilation of Fuel Characteristic Classification System (FCCS) fuel loading data and population of the FCCS database. FCCS fuel type aggregation decisions were made, and documented, to best represent and quantify fuel loadings for specific and general fuelbed types. Methods developed to compile and record data have been documented so new data sets can be efficiently integrated into the database as they are developed.* • *Most of the largest and most appropriate data sets on fuel loads have been ingested into the system. Distribution functions for each type/strata are being created. Decisions related to how to group fuelbeds are on-going and will lead to a better understanding of the data available and the gaps in information for emissions modeling.* • *The database will be used to work toward developing ways to map and validate fuel loadings and to assess the statistical characterization of fuel loadings by type.*	Ongoing
Southern Integrated Prescribed Fire Information System for Air Quality and Health Impacts	Talat Odman 16-1-08-1	• *Develop an integrated prescribed fire and air quality information system for the southern US, that includes prescribed burn and air quality data; and results from air quality, smoke exposure and human health effects modeling.* • *System will be designed to dynamically update data going forward.*	Ongoing

Emissions Inventory

A smoke emission inventory is an account of the contribution smoke makes to the loading of specific chemicals in the atmosphere. There might, for example, be an inventory of all smoke, of smoke from agricultural burning, of smoke from prescribed burning or of smoke from wildfires. And for each of these there might be an inventory of carbon dioxide, size segregated particulate material (PM10 or PM2.5), VOC (volatile organic carbon), and a host of other chemicals. Obviously there are both temporal and spatial dimensions for each of these accounts. An inventory might be associated with a specific event, e.g. a wildfire, with a period of time, a week, month or year, with a specific location, a National Forest, a county or a State and so forth. So, in general, an inventory may have a number of dimensions such as: time, space, emitted chemical and fire type perhaps being the most common. Inventories are constructed from "emission factors" which are the amount of the specific chemical species is emitted into the atmosphere divided by the amount of the "fuel" consumed by the fire. Emission factors, obviously, are rather complex. They would be expected to be a function of the nature of the fuel, environmental factors and efficiency of fuel combustion as well as other things. Emission factors are measured quantities; they are determined from observations collected on many different burns and hence are statistically determined with a central value and an uncertainty distribution. The emission factor typically is a mass per unit mass number, e.g. x grams of an emitted species/kg of fuel burned. The inventory is then constructed by identifying the mass of fuel consumed by the fire over appropriate time and space dimensions then multiplying it by the emission factor (Figure 2). Building the inventory involves adding up all the emissions for each chemical species for the times and locations of interest.

SMOKE EMISSIONS INVENTORY

So, in general, an inventory may have a number of dimensions such as: time, space, emitted chemical and fire type perhaps being the most common. Inventories are constructed from "emission factors" which are the amount of the specific chemical species is emitted into the atmosphere divided by the amount of the "fuel" consumed by the fire. Emission factors, obviously, are rather complex. They would be expected to be a function of the nature of the fuel, environmental factors and efficiency of fuel combustion as well as other things. Emission factors are measured quantities…

As stated above, in the USA inventories are developed for different purposes. An inventory of an individual fire might be used to calculate the impact of that specific fire. More often the impact of a future fire or set of fires might be estimated using a hypothetical inventory and modeling the fire's impact. In the United States, the US Clean Air Act has established a framework for air quality

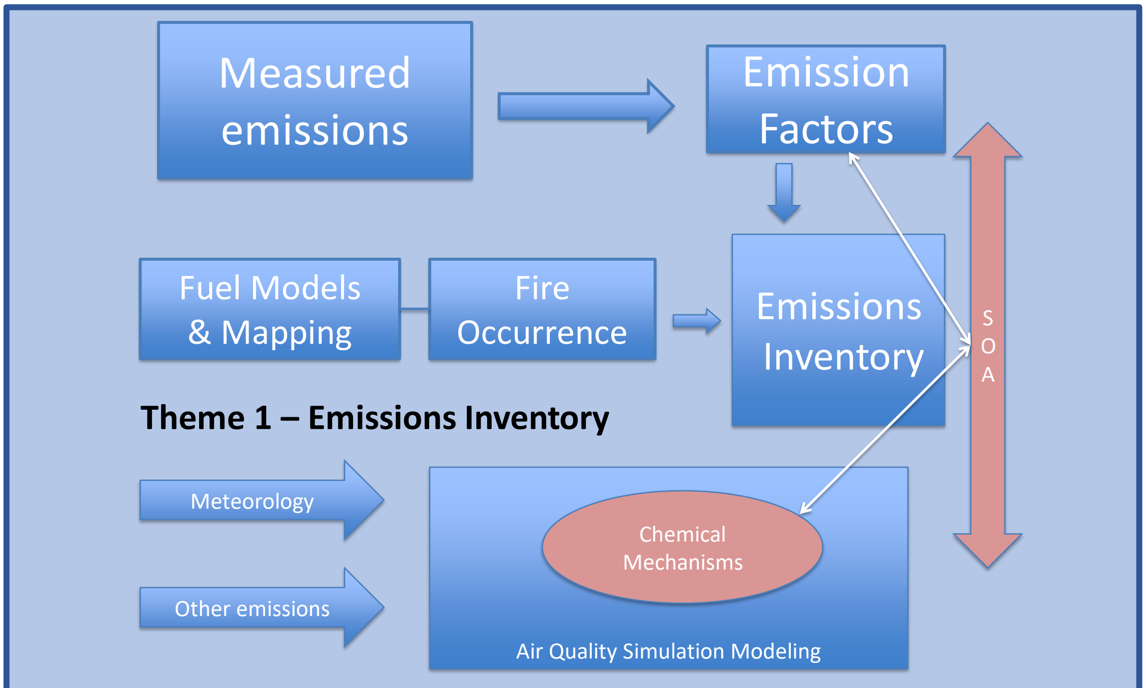

Figure 2: Smoke emissions inventory includes a number of steps and data needs.

management that depends on retrospectively identifying the contribution individual sources and category of sources, e.g. agricultural burning, prescribed burning, wildfire make on the "ambient" air quality of a region, generally a county. National Ambient Air Quality Standards (NAAQS) are set based on considerations of human health impacts for CO, SO2, NOx, Lead, Ozone and PM (smaller than 10 and 2.5 micrometers in diameter). The Act requires States to measure ambient air quality and to develop "State Implementation Plans (SIP)" to identify mechanisms to reduce emissions where the NAAQS are not being met and to ensure that emissions growth will not lead to NAAQS exceedance in future. Emission limitations and reductions are based on the results of air quality models that are driven by emissions inventories that include industrial, energy, transportation, and smoke emissions. Hence, the validity and accuracy of the emissions inventory is of paramount importance in air quality management (Riebau & Fox, 1987).

Smoke emission inventories have become increasingly important in the 21st century. Climate change issues are increasingly calling for improved greenhouse gas emission inventories. Needs for greenhouse inventories are moving from a general accounting for fire contributions toward project, or individual fire level accounting of emissions. More obviously human caused pollution sources (e.g. industry, transportation and energy generation) have had increasingly stringent emission reductions enforced, which has resulted in improved air quality. However, improved scientific understanding on air quality impacts to human health has also led to tightening of the NAAQS, especially for Ozone and PM2.5. Fire smoke has emerged as a source that is receiving greater attention because other sources have been more controlled. In addition to the NAAQS, the Clean Air Act also has led to a "Regional Haze Program" to protect visibility in cleaner areas of the country, specifically federally managed lands with special designation such as

National Parks and Wilderness Areas (Fox et al., 1999). The RHP also requires SIPs to improve visibility and fire has been identified as a significant contributing source to visibility impairment. The result of all this is an increase in the consideration of smoke sources by regulatory agencies. This consideration takes the form of using Emission Inventories and air quality modeling to quantify smoke impacts and examine potential for emissions limitations and reductions. Thus, it is in the interest of fire programs to develop the very best, most accurate and most scientifically defensible smoke emissions inventories. For this reason JFSP's SSP has addressed research toward fundamentally improving emissions inventories.

UNERTIANITIES IN FIRE EMISSIONS INVENTORIES

A management implication of the project *"Critical Assessment of Wildland Fire Emissions Inventories: Methodology, Uncertainty, Effectiveness"* is that fuel consumed is the greatest source of uncertainty in forest fire emission inventories. Improved mapping of forest fuel loading using FIA plot data and differentiated by forest type distributions within burned pixels could reduce the uncertainty of FEIS

JFSP Science for Building an Inventory

SSP research on this theme has developed new science and knowledge to help support and define an accurate national wildland fire emissions inventory system. At the present time, there are a number of different smoke inventories mechanisms. Two SSP projects address the construction of smoke emission inventories. *Critical Assessment of Wildland Fire Emissions Inventories: Methodology, Uncertainty, Effectiveness* (Hao 12-1-7-01) critically reviewed and quantified some uncertainties of current fire emissions inventory systems (FEIS) and the major components used for estimating wildland fire emissions. They attempted to consider cost-effective improvements for each FEIS however this proved problematic. The project developed a "reference" dataset and an associated "Reference Emission Inventory" by using detailed site-specific information such as FIA data plots, the Rangeland Vegetation Simulator and enhanced satellite products. They then made detailed statistical comparisons of differences between the REI and three of the major FEIS. These results indicated significant bias and errors in each of the three FEIS. Urbanski and others presented some of these results at the International Association of Wildland Fire 2nd International Smoke Symposium (ISS2). He utilized the information in the "Reference Emissions Inventory" to develop a new "Missoula Fire Lab Wildfire Emission Inventory (MFLEI)" which is a retrospective, daily wildfire emission inventory for the contiguous United States produced using multiple datasets of fire activity and burned area, a newly developed wildland fuels map and an updated emission factor database. The fuel type classification map is a merger of a national forest type map, produced by the USFS Forest Inventory and Analysis (FIA) program and the Remote Sensing Applications Center (RSAC), with a shrub and grassland vegetation (rangeland) map developed by the USFS Missoula Forestry Sciences Laboratory (Reeves & Mitchell, 2011). Forest fuel loading is from a fuel classification (Keane et al., 2013) developed from a large set (> 26,000 sites) of FIA surface fuel estimates. Herbaceous fuel loading is estimated using site-specific parameters with Normalized Differenced Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS). Shrub fuel loading is quantified by applying numerous allometric equations linking stand structure and composition to biomass and fuels. These structure and composition data are derived from canopy cover, canopy height, and species composition data from the LANDFIRE Project (www.landfire.gov). The MFLEI estimates of NAAQS air pollutants and volatile organic compounds VOCs is evaluated with respect to anthropogenic emissions reported in the US EPA National Emission Inventory. A management implication of this project is that fuel consumed is the greatest source of uncertainty in forest fire emission inventories. Improved mapping of forest fuel loading using FIA plot data and differentiated by forest type distributions within burned pixels could reduce the uncertainty of FEIS.

Assessment of Prescribed Fire Emissions and Inventories (Larkin 12-1-7-02) is conducting a comprehensive assessment of systems that produce fire emissions information and creating a catalogue describing each fire emissions system including its use, capabilities and limitations and creating a technical repository to document each fire emissions system in this catalogue. A presentation at ISS2 discussed progress of 12-1-7-02 and concluded that, in the south-eastern US small fires dominate the fire emissions and so need to be included in any inventory; reasonable efforts to catalogue small fire activity can be made using satellite data (set to improve with VIIRS); and statistical modeling seems to have the ability to improve the inventory. However, this later improvement needs further testing. This project has a completion date of May 2017.

A closely related ISS2 presentation, *2014 Wildland Fire Emissions Inventory for the U.S.* by Shih Ming Huang and others, overviews the most current of EPA's tri-annual National Emissions Inventory (NEI) that details the annual emissions of criteria and hazardous air pollutants (HAPs) from all sources, including wild and prescribed fires. Wildland fires are the top emitting source category of PM2.5 in the latest (2011) NEI, accounting for 33% of PM2.5. The 2014 NEI will be the second time state/local/tribal (SLT) fire activity data will be incorporated. About 50 fire activity datasets submitted by SLT agencies, will be evaluated for data quality, and reconciled with multiple national/regional fire activity data sources using the SmartFire2 system. Daily fire activity data will be processed through the BlueSky Framework to estimate fuel loading, fuel consumption, and smoke emissions with the Fuel Characteristic Classification System, CONSUME, and Fire Emission Production Simulator respectively. The emissions data from this inventory were presented. On a similar note, a poster at the ISS2 *The 2014 National Emission Inventory for Rangeland Fires and Crop Residue Burning* by Pouliot et al. presented an improved methodology utilizing satellite HMS data, National Agricultural Statistics Service data, and State inputs to increase the accuracy of the emissions estimates.

Three other SSP projects had significant progress associated with improving, evaluating and applying fire emissions inventories. *Deterministic and Empirical Assessment of Smoke Contribution to Ozone – DEASCO3* (Moore 11-1-6-06) has built unique and flexible tools within a web map browsing environment that give managers a variety of spatially oriented ways to interrogate fire data, ozone monitoring data, fire emissions inventories and modeling results. Complex technical analyses of historic fire events are transformed into instructive tables, charts and maps that help describe how and to what extent fires contribute to ambient ozone concentrations. The DEASCO3 project created a dynamic and accessible web-based tool that allows resource managers to participate more fully in ozone air quality planning efforts with state and federal air regulators. A follow-on project was designed to extend the DEASCO3 concept to deal with particulate matter.

Particulate Matter Deterministic and Empirical Tagging and Assessment of Impacts on Levels – PMDETAIL (Moore 12-1-8-31) will quantify impacts of prescribed and other fire sources on particulate matter (PM) levels across the continental US. It is developing new fire emissions inventories and computational modules for chemical transport models to simulate the atmospheric transformation of these emissions, and evaluate them against field measurement. It is building a PM exceedance vulnerability matrix (P-EVM) that will rank-order the potential impact of prescribed fire emissions by location. These tools were demonstrated at a Workshop during the ISS2 titled "Developing Strategies for Prescribed Fire under new US Ozone and PM Standards and Exceptional Event and Regional Haze Rules using recently developed tools." This Workshop provided an overview of contemporary and emerging Federal and state regulations and demonstrated successful exceptional event experiences. This project was scheduled for completion in September 2016 but at this time is just being concluded.

Synthesis of Comprehensive Emissions Measurements and Multi-scale Modeling for Understanding Secondary Organic Aerosol Chemistry in Wildland Fire Smoke Plumes (Barsanti 14-1-03-44) will provide improved emission factors (EF) for wildland fuels with an emphasis on capturing precursors to secondary organic aerosols (SOA); develop and apply a process-level box model that explicitly describes the reactions leading to SOA formation and aging, and; deliver an operational modeling framework accessible to air quality and land managers with an improved ability to detect SOA formation, and thus fine particulate matter (PM2.5) from wildland fires. In turn this will evaluate contributions of biomass burning to SOA in the Pacific Northwest and document the magnitude of change in SOA and PM2.5 relative to the 2011 National Emissions Inventory. Barsanti presented some preliminary results of this research at ISS2. Chemical transformations of non-methane organic gases (NMOGs) emitted from biomass burning lead to the production of ozone and secondary particulate matter (SOA). They created the most comprehensive NMOC emission factor database to date by compiling data from multiple advanced, analytical approaches. Until recently, a significant mass fraction of NMOGs in fire emissions (up to 80%) had remained uncharacterized or unidentified and not represented in emission inventories. Advanced analytical techniques enabled identification and quantification of an unprecedented fraction of fire NMOGs allowing "speciation profiles" (needed for model inputs) to be created and evaluated in models. Some NMOCs (including SOA precursors) likely are partitioned between the gas and particle phases, and thus their gas-phase emission factors will vary with particle loading. In box models, predicted gas- and particle-phase pollutants and precursors are very sensitive to changes in the emissions inventories and subsequent changes in surrogate species profiles. In regional air quality models, ozone and SOA formation are also somewhat sensitive to changes in emissions inventories; in some cases, maximum predicted SOA concentrations doubled with changes to emissions inventories/surrogate profiles. Work needs to continue on refining the model mechanisms to be sure these enhanced emission profiles are being properly simulated. This project is scheduled for completion in 2017.

Although not a JFSP funded project the Department of Energy recently has conducted some field research comparing ground level and aircraft measurements of fire plumes in the eastern and western US. One presentation at the ISS2 provided a preliminary analysis of some data. *Biomass Burning Observation Project (BBOP): Near Field and Regional Evolution of BB Emissions* by Sedlacek and others presented preliminary results from a 2013 summer and autumn coordinated field campaign that combined aircraft measurements and ground observations to investigate both near-field and regional evolution of biomass-burning (BB) aerosol particles. Some preliminary results suggest fire plumes are dominated by organic aerosol, with soot accounting for only a few percent of mass. Organic aerosol mass remained constant while chemical composition changed rapidly. O:C and OM:OC increases while primary BB aerosol markers decrease. There are rapid, large increase in aerosol nitrate but none in sulfate. Ozone concentrations are highly variable from plume to plume. BBOA chemical properties appear to be strongly correlated with modified combustion efficiency (MCE). The results of this study should be very helpful in informing the development of the Fire and Smoke Modeling Evaluation Experiment (FASMEE: see next section of this report for explanation of the FASMME project) plans.

JFSP Science for Emission Factors (fire type and intensity, speciation & magnitudes)

SSP research dealing with emission factors has focused on improving the science needed to construct a valid emissions inventory. Three projects have contributed directly to the generation of improvised emission factors. *Experimental Determination of Secondary Organic Aerosol Production from Biomass Combustion* (Collett 09-1-3-01) measured increases of approximately 70% in fine particle mass as smoke plumes "age" at the Missoula fire chamber. These observations suggest that emission factors need to be refined to account for VOC precursors emitted from burning which increase PM2.5 concentrations downwind. *Influence of Fuel Moisture and Density on Black Carbon Formation During Combustion of Boreal Peat Fuels* (Benscoter 11-1-5-16) showed that remote sensing applications can be used for estimating peat land water table position and surface soil fuel moisture, which can inform fire behavior assessment models. The threshold of 200% GWC can be used to structure prescribed or wildland fire decisions to minimize the likelihood of burning when direct measurements or indirect indices suggest a high smouldering risk due to low peat fuel moisture content. Although not supported by JFSP, a presentation at ISS2 *Review of Causes and Impacts of Regional Haze Episodes from Smoldering Peat Fires* by Rein and Hu addressed peat land fires that contribute more than 15% of annual global carbon emissions. But smouldering which produces the majority of the emissions is not well studied and its emissions require more study. Another ISS2 presentation, *Aerial Sampling of Emissions from Biomass Pile Burns in Oregon* by Aurel and Yonker, measured emissions from burning timber slash piles covered and not covered with polyethylene sheets. Results showed that wet uncovered piles burned with lower combustion efficiency resulting in higher emissions than the covered piles.

DEASCO3 AND PMDETAIL

One of the primary advantages of the systems prototyped in these two projects is that they directly involve and incorporate State regulatory agency considerations into the emissions inventory system. We are hopeful that States and other regulatory agencies will work with federal land managers to evaluate, improve, and eventually adopt the concepts developed in this research.

One ongoing SSP study *Phase Dynamics of Wildland Fire Smoke Emissions and their Secondary Organic Aerosols* (Kreidenweis14-1-03-26) is conducting a comprehensive examination of how dynamics of plume dilution affect the timescales and mechanisms of SOA precursor release and oxidation, a key uncertainty in determining appropriate emission factor and subsequently modeling fire-derived SOA. Preliminary results from this research were presented at the ISS2. An aerosol microphysics model of aerosol size, volatility, and chemistry was applied to estimate the influence of vapor wall loss on the SOA formation in the FLAME-III smog-chamber studies. Simulations show that the mean OA enhancement is 1.8 throughout the experiments when considering vapor wall loss, which roughly matches the mean observed enhancement during FLAME-III. On the other hand, the mean OA enhancement increases to over 3 when wall loss is turned off, which implies that the vapor wall losses are suppressing SOA formation. These results are generally robust across the parameter uncertainties (wall-loss and mass-transfer coefficients, and chemistry assumptions) (Bian et al., 2016).

Other studies are contributing science to the determination of emission factors. The Barsanti and Moore projects each have significant elements of work addressing emission factors and their use for characterizing SOA resulting after smoke plumes age in the ambient atmosphere.

JFSP Science for Inventories in Use (Regional Ozone & PM)

SSP research has contributed to improved fire emissions inventories, to the use of those inventories to evaluate fire contributions to regional ozone and PM loadings and has outlined steps needed to produce an accurate, ongoing national wildland fire emissions inventory system. Many of the projects funded under the Emissions theme of the SSP have or will make contributions to this objective.

Progress has already been discussed for *Critical Assessment of Wildland Fire Emissions Inventories: Methodology, Uncertainty, Effectiveness* (Hao 12-1-7-01) and *Assessment of Prescribed Fire Emissions and Inventories* (Larkin 12-1-7-02) which, when completed, should, respectively, provide information about more efficient and cost effective ways to build an inventory and provide a catalogue of emission inventory systems for ready reference to users.

Deterministic and Empirical Assessment of Smoke Contribution to Ozone – DEASCO3 (Moore 11-1-6-06), *Particulate Matter Deterministic and Empirical Tagging and Assessment of Impacts on Levels – PMDETAIL* (Moore 12-1-8-31), and *Synthesis of Comprehensive Emissions Measurements and Multi-scale Modeling for Understanding Secondary Organic Aerosol Chemistry in Wildland Fire Smoke Plumes* (Barsanti 14-1-04-16) are each using wildland fire emission inventories to assess fire's contributions to regional air quality. The completed Moore project provides valuable information about the contribution wildland fire has made to regional ozone loadings on a national basis. Further it and its companion project, the soon to be completed PMDETAIL project, provide an outline of the types of components needed to develop an improved accurate and quality assured national emissions inventory system. One of the primary advantages of the systems prototyped in these two projects is that they directly involve and incorporate State regulatory agency considerations into the emissions inventory system. We are hopeful that States and other regulatory agencies will work with federal land managers to evaluate, improve, and eventually adopt the concepts developed in this research.

An ongoing study, *Mapping Fuels for Regional Smoke Management and Emissions Inventories* (French 15-1-01-1), is developing methods to map and validate wildland fuel loading for emissions modeling whilst incorporating spatial and temporal variation at multiple scales in order to build and distribute geospatial fuels and emissions products for regional and national smoke management and emissions inventories. They are also evaluating sources of uncertainty and data gaps for emissions estimates using a sensitivity analysis of emissions models to fuel variability informed by distributions of fuel characteristics. A presentation at ISS2, *Developing the Next Generation of Fuelbed Data on Fuel Loadings Useful for Emissions Modeling* by French and others, presented the progress to date on this project. They completed characterizing the distributions of fuel loadings by strata for standard FCCS fuelbeds along with their spatial variation. They described analyses to quantify sensitivity of emission estimates to variability in fuel loadings while building an information system to display their results. The database will now be used to develop ways to map and validate fuel loadings and assess the statistical characterization of fuel loadings by type. The validation exercise will provide a way for managers to know the reliability of the data in specific forests or regions, and the statistical assessment will provide modellers of emissions and smoke a way to include an uncertainty metric in emissions data outputs.

Although not a JFSP funded project, a presentation at the ISS2 *Evaluation of Revised Emissions Factors for Emissions Prediction and Smoke Management* by Prichard and others evaluated use of Urbanski's 2014 emission factors in Consume and FOFEM using data collected from earlier studies in southeast and southwest conifer forests, western shrublands, grasslands, and boreal forest wildfires. They concluded that model-specific estimates of flaming and smoldering, which generate quite different amounts of emission, complicated the ability to assess changes. Fire average short term flaming and smoldering factors should be used in the models and whilst using separate fuel type and combustion phase emission factors should improve emissions estimates more research is needed.

How is This Theme's Information Being Used?

- Work completed under this theme has directly influenced the EPA's National Emissions Inventory (NEI) and reduced conflicts over fire emissions as regards to air quality.
- Research from this theme has improved emissions calculations in WFDIS and other agency fire planning systems.
- Systems/research developed under this theme are directly influencing and being used in the development of state implementation plans (SIPs) for Ozone and particulates and in support of exceptional event determinations.
- Work supported under this theme is being used to improve air quality assessments for secondary organic aerosols in determining both ozone and PM2.5 standard compliance by the states and EPA.

Remaining Challenges

Emissions inventories are by their nature complex, uncertain, and often controversial. In recognition of this, regulatory agencies that require emissions inventories often focus on establishing rules for data consistence and seek to be as inclusive as possible. In the case of wildfire emissions, there remain a number of inconsistencies in the reporting process, different ownerships report fire characteristics differently, fuel loadings are uncertain, combustion processes are dependent on a number of variables that can be estimated differently, wildland fire combustion varies over the period of the burn, and extraneous environmental factors play a significant role. Until a nationally implemented fire inventory methodology is applied across all ownerships and fire types (wildfire, prescribed fire, agricultural burning) there will remain significant inconsistencies between different inventories and uncertainties potentially leading to bias. Attempts to avoid this have looked toward satellite remote sensing as a more objective means of observing fire activity. This has greatly improved inventories but detection issues limit the utility of this approach. Involving State regulatory agencies in post fire analysis, for example, to ascertain if a planned burn was actually accomplished, if it was of the size that had been planned and did it occur where and when it had been planned, has helped improve the accuracy of emissions inventories. While our research projects have addressed all of these issues, it remains for the agencies that have vested interests in fire, land management, and air quality protection to agree on procedures and approaches to develop a repeating quality assured process for generating an annual national wildland fire emission inventory. Many of the tools needed for this have been developed and applied in SSP research projects and a number of presentations at the ISS2 identified above support this.

The precise chemical nature of fire emissions and their evolution in the atmosphere is also an extremely complex issue. Not only is the specific mix of chemicals emitted from a fire complex, but because many of the hydrocarbons emitted exhibit different degrees of volatility, participate in phase changing chemical reactions and have differential hygroscopic properties, many uncertainties remain. The recent past has seen considerable progress on measuring fire emissions in the laboratory but how such laboratory information relates to actual field conditions remains quite uncertain. The ongoing research of the FASMEE program will shed light on these issues, but many fruitful research opportunities are likely to remain for many years to come.

A key question, however, is just how much understanding of the complex chemistry of evolving fire smoke is needed for smoke and air resource management purposes. If our propose is to accurately assess the contributions of wildland fire to ambient air quality, then a full understanding of all the complex chemistry may not be needed. Hopefully completion of the ongoing Moore, Kreidenweis and Barsanti projects will help us answer this question.

SSP THEME II – FIRE AND SMOKE MODEL VALIDATION

The objective of the fire and smoke model validation theme is to identify the scientific scope, techniques and partnerships needed to objectively validate smoke and fire models using field data. Since the plan's implementation in 2011 and before the plan itself, 10 projects had been funded and completed in this area. Completed projects have addressed: A) weaknesses in existing smoke models and what data are needed to improve them, B) investigated the mechanisms of plume rise and super fog formation, C) developed data sets and a framework comparing existing smoke model performance, D) evaluated the smoke consequences from both low and high intensity burns, and E) laid the groundwork through the development of an interagency plan for a new research effort, the Fire and Smoke Model Evaluation Experiment (FASMEE), which will collect field data over a multi-year series of large multi-discipline multi-agency field experiments; this effort will be the largest and most complex set of smoke model validation field experiments which the JFSP has ever undertaken, but it will be done in partnership with DOD, NOAA, NASA, EPA, USDA Forest Service, and others. Under the SSP major new insights have been gained into areas of smoke modeling that are weakest, such as plume dynamics and combustion physics as influencing factors to emissions. Additionally, research has demonstrated that small, low-intensity fires and large, high-intensity fires generate different smoke chemistry regimes, generally not considered by most current models but which have different consequence for secondary organic aerosols (SOA), fine particulate emissions, and ozone creation. One area, which has been highlighted, is the growing need to recognize the differences which plume injection height estimates can make in smoke trajectories, an issue which has plagued smoke modeling accuracy for many years. JFSP funded work on model evaluation/validation has already resulted in changes in the EPA's National Emissions Inventory (EPA NEI) as it regards wild land fire. It has also resulted in improvements to the BlueSky smoke modeling framework (which was developed originally with JFSP support in partnership funding with others) and also NASA smoke satellite and modeling products. SSP research under this plan theme will have a lasting significant impact on how fire, especially prescribed fire, will be treated in future smoke/air quality model development.

FASMEE

FASMEE is a multi-agency effort to 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. (see: https://www.fasmee.net/)

The objective of the fire and smoke model validation theme is to identify the scientific scope, techniques and partnerships needed to objectively validate smoke and fire models using field data. Dispersion modeling is fundamental to air quality management (Riebau & Fox 1987; Strand et al., 2017). For example, State Implementation Plans (SIPs) that regulate air pollution sources are built using modeling and before any new stationary sources are built, a modeling analysis is done to ensure that emissions from the source will not violate standards. For smoke, at least three distinct types of dispersion modeling approaches are needed. One type is for real time (or as close as possible to real time) smoke emissions used to provide health warnings and assess other on-going air quality related impacts. The second type is a retrospective modeling analysis for regulatory purposes, using fire emissions data corrected and quality-assured after the fire has occurred to help quantify fire impacts on the measured air quality during and following fire events. This quantification is needed for both planning of future emissions limitations (State Implementation Plans) and for segregating human from natural contributions (Exceptional Events Policy). A third type of smoke modeling is modeling before a prescribed fire is conducted to obtain a permit to burn or deciding on best practices to minimize smoke impacts. Of course, this is a broad simplification but clearly these three smoke modeling categories address different scientific questions and relevant time and spatial scales (Fox & Riebau, 2000; Battye & Battye, 2002).

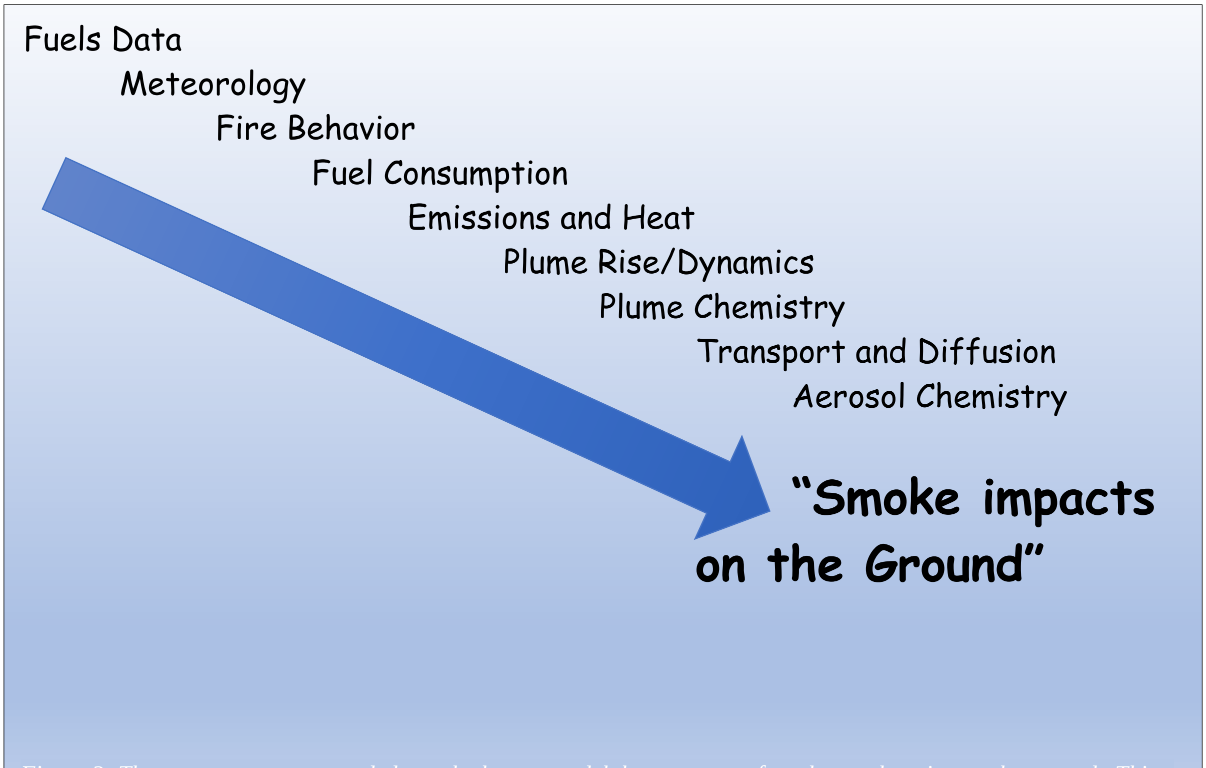

Figure 3: There are many steps needed to calculate or model the transport of smoke to a location on the ground. This is a very simplified view of those steps, each one often requiring one or more computer models.

These modeling categories sometimes use the same smoke dispersion models or different models, and, each may use different types and sources of data even with the same model. All models must have as input smoke emissions, but to calculate emissions and their ultimate impacts downwind a series of other models must be employed (Figure 3). The result is smoke modeling exercises are not able to recreate or represent "reality" for any particular location at any specific time. As the number of models employed and consequent complexities escalate, invariably uncertainties and errors are propagated. The dilemma is that increasing complexity to achieve greater accuracy sometimes results in increased errors, if only under certain conditions.

However, as the models have improved, they are showing greater skill in depicting general trends and a clearer picture of the potential magnitude of on the ground impacts. (Goodrick et al., 2012; Larkin et al., 2012). The importance of gains in skill in these should not be underestimated, as they are extremely important for planning, permitting, and public health warnings. But understanding how to improve models, and indeed the complex 'chain' of models used in smoke dispersion simulation, has been impeded by lack of data sets of appropriate type and scale (Garcia-Menendez et al., 2014; Larkin et al., 2013). To illustrate, the complexity of these needs (stated as questions) include:

1. How does fire intensity and spread actually effect fuels consumption and emissions both physically and chemically;
2. How does fire intensity and spread effect plume rise and chemical transformations within plumes;
3. What factors influence and control the formation of multiple plume 'cores' and determine smoke injection height;
4. What meteorological and burning conditions determine super-fog events;
5. Do woody species and grasses really burn so similarly that both can be modelled using the same tools;
6. What are the chemical and physical changes smoke under goes during long-range transport and what factors control these changes;
7. Does the mix of vegetative species influence smoke emissions and chemistry, and if so, how critical are such influences;
8. Where are the greatest and the most acceptable errors in smoke models and how may they be reduced;
9. What types and amounts and at what geographic scales does data need to be collected to validate the many modeling steps involved in smoke modeling;
10. Can and how might an interagency cooperative effort be developed to validate/test/develop smoke models?

As the SSP draws to a close, JFSP projects have addressed all these questions either directly or, tangentially. Some of the projects were started by the JFSP prior to the SSP being devised to guide the line of work. The specific projects that have been funded are presented in Table 3.

Table 3: JFSP projects funded that address model validation. Details of projects including final reports can be accessed through the JFSP website: https://www.firescience.gov/index.cfm

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Fire and Smoke Model Validation Theme	Status
Validation of Fuel Consumption Models for Smoke Management Planning in the Eastern Regions of the United States	Roger Ottmar 08-1-6-01	• CONSUME and FOFEM predict consumption accurately for shrub and herbaceous layers • Fine woody fuels, litter and duff consumption need improvement. Fuel consumption datasets compiled into one.	Completed
Evaluation of Smoke Models and Sensitivity Analysis for Determining their Emission Related Uncertainties	Talat Odman 08-1-6-04	• DAYSMOKE correctly predicted near-fire fine particulate matter ($PM_{2.5}$) concentrations and plume rise. Also injected smoke into correct vertical layer. • DAYSMOKE can be turned into a reliable smoke impact prediction tool for managers to use within short distances of a burn unit. • On a regional scale, $PM_{2.5}$ impacts can best be predicted with air quality models like CMAQ. Alternative versions, such as AQ-CMAQ show promise for better predictions but need further development.	Completed
Evaluation and Improvement of Smoke Plume Rise Modeling	Yong Liu 08-1-6-06	• DAYSMOKE was the most promising model for correct plume height simulation. Simpler plume rise simulations overestimated smoke plume height. • Predictions from DAYSMOKE were improved by including a new property, multiple updraft core number. • Current models widely used in smoke management were shown to overestimate plume rise for prescribed burns in the Southeast. This would affect downwind air quality predictions.	Completed
Airborne and Lidar Experiments for the Validation of Smoke Transport Models	Shawn Urbanski 08-1-6-09	• New info on carbon dioxide (CO_2), $PM_{2.5}$ and ozone (O_3) precursors could affect emissions inventories. • Combustion efficiency found to be important in determining emissions. Dispersion and plume rise measurements will aid in smoke model evaluation.	Completed
Creation of a Smoke and Emissions Model Intercomparison Project (SEMIP) and Evaluation of Current Models	Sim Larkin 08-1-6-10	• Errors in fire activity information have a critical impact on fire and emissions modeling. • Diurnal emissions profile has huge, non-linear effects on magnitude and location of emissions but is not well represented in fire behavior models. • Plume rise calculations are important in smoke dispersion and downwind concentrations and differences in these calculations lead to vastly different patterns and magnitude of ground level smoke. • New observation campaigns targeted toward developing test cases in areas of limited understanding could lead to improvement in emissions and smoke dispersion estimates. • An open-access platform for collaborative modeling and evaluation (such as SEMIP) would maintain baseline comparison test cases and ensure that standard comparisons between models and model validation can be performed.	Completed

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Fire and Smoke Model Validation Theme	Status
Development of Modeling Tools for Predicting Smoke Dispersion from Low-Intensity Fires	Warren Heilman 09-1-4-01	• Plume heights associated with low-intensity fires beneath forest canopies can be highly variable with increased resultant variability of downwind plume heights. • ARPS-CANOPY (a complex forest canopy flow simulation modeling system) coupled with FLEXPART Lagrangian particle dispersion model is a potential predictive smoke modeling tool option for fire managers requiring detailed smoke dispersion information. • LIDAR technology for characterizing forest vegetation structure/architecture needs to be incorporated into future fire-fuel-atmosphere interaction monitoring studies in order to improve parameterizations of canopy effects on atmospheric circulation in coupled fire-atmosphere and smoke prediction models.	Completed
Sub-Canopy Transport and Dispersion of Smoke: A Unique Observation Dataset and Model Evaluation	Tara Strand 09-1-4-02	• Identified best modeling pathway within the BLUESKY framework to operationally predict smoke concentrations from low-intensity burns. • BLUESKY predictions for low intensity burns are improved by incorporating planned start and end times for burns, as well as flame length limitations. • Observed fuel loads did not improve predictions enough to warrant the expense and time to measure. • Fire managers could reduce the potential for unwanted smoke impacts by ending ignition earlier in the day, allowing more time for mixing and movement of smoke away from the forest floor and mitigating the amount of smoke trapped under the forest canopy.	Completed
Superfog Formation: Laboratory Experiments and Model Development	Marko Princevac 09-1-4-05	• Theory and experiments elucidate the conditions necessary for Superfog formation. • Two-dimensional Superfog Assessment Model (SAM) developed that predicts likelihood of Superfog formation at burn site. • SAM must be coupled with another model, such as PB-Piedmont, to predict the spread of Superfog.	Completed
Data Set for Fuels, Fire Behavior, Smoke and Fire Effects Model Development and Evaluation (RxCADRE)	Roger Ottmar 11-2-1-11	• The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) collected fire data on large and small operational burns and successfully developed synergies between fuel, atmospheric conditions, fire behavior, radioactive power and energy, smoke and fire effects measurements; critical inputs to fire model development and evaluation. • Found that longer-term intense burns in complex and heavy fuels will be required to successfully validate and improve smoke and air quality models.	Completed

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Fire and Smoke Model Validation Theme	Status
Sensitivity Analysis of Air Quality to Meteorological Changes in Fire Simulations	Talat Odman 12-3-1-06 (GRIN)	• The ability of current air quality models to replicate the impacts of wildland fires may be limited by the capability of existing numerical weather prediction systems. • Improvements in meteorological modeling should be considered as one of the goals in any strategy designed to improve fire-related air quality simulations. The limitations in these simulations cannot be overcome solely by improving emission rates.	Completed
Fire and Smoke Model Validation Workshop	Tim Brown 13-S-01-01	• Produced the "National Plan for Validating the Next Generation of Wildland Fire and Smoke Models for Operations and Research Use". • The Fire and Smoke Model Evaluation Experiment (FASMEE) is a direct result of the National Plan. FASMEE is an interagency collaboration designed to implement an operational-scale set of experimental prescribed fires yielding an integrated, large-scope, multi-discipline dataset for the purpose of evaluating and validating wildland fire behavior and smoke models.	Completed
Fire and Smoke Model Evaluation Experiment (FASMEE) – Phase I	Roger Ottmar 15-S-01-01	• Preparation of the Phase I Study Plan, including designation of leads for each section of experiment. • Selection of potential study sites is well underway.	Ongoing

In recent years air quality modeling in general and air quality forecasting in particular have received considerable attention. This has led to significant progress intersecting with the smoke science plan in both this Model Validation theme and the Smoke and Populations theme. Some of this is summarized in our discussion of progress under the active JFSP research project *US Smoke Hazard Warning System: Prototype and Enhancements to Operational Systems* (Larkin 15-1-02-4). A special session at the ISS2 conference in November 2016 addressed Smoke Forecasting Systems and included an overview by Larkin of this project as well as presentations by Davignon from Environment and Climate Change Canada, and Huang and Stajner from NOAA describing progress on operational smoke forecasting systems. The Canadian system is detailed in a recent publication (Radenko et al., 2016.) The NOAA system involves an effort by over 10 different groups in NOAA and EPA with assistance from the Forest Service to provide a national air quality forecasting capability that predicts smoke, ozone and, most recently, PM2.5. NOAA, in the aforementioned presentations, identified the following continuing challenges for their operational system: improved source characterization, including temporal fire emissions; improved VOC and aerosol chemistry mechanisms; better plume rise simulation; more dynamic fuel characteristics, and; validation of smoke predictions and impacts.

JFSP Science for Smoke Model Validation

SSP research on this theme has developed new science and knowledge to help validate fire and smoke models. For JFSP, an on-going concern has been fuels consumption during fires for fuels management and also for smoke (Ottmar et al., 2011). One result is that these models generally are hindered by the lack for accurate fuel loading data, especially data that represents the distribution of fuel loading across the fire area (Ottmar 08-1-6-01, Odman 08-1-6-04, Larkin 08-1-6-10). Another result suggests that plume rise is often over-predicted by commonly used simple techniques, which miss the influence of multiple plume cores, and result in significant errors in predicting smoke transport (Odman 08-1-6-4, Liu 08-1-6-06, Larkin 08-1-6-10, Heilman 09-1-4-01). Diurnal meteorological patterns and down-valley flows need to be understood if reliable smoke transport and super-fog predictions are to made (Princevac 09-1-405, Larkin 08-1-6-09). Smoke emissions and smoke transport sub-canopy predictions might be improved by use of Lagrangian particle dispersion models and smoke reduced by earlier in the day ignitions (Heilman 09-1-4-01, Strand 09-1-4-02). Projects have also learned that smoke chemistry has a very large, if rather misunderstood, role in emissions and emissions inventories, somewhat up-setting accepted ideas on fire smoke emission factors (Urbanski 08-1-6-09). Perhaps most importantly JFSP has verified that the more models are tested in the field or running them through post-fire scenarios, the clearer it becomes that there is a need for more and better data sets to evaluate them (Larkin 08-1-6-09). It was also verified that fuels consumption, fire behavior, and meteorology models must be evaluated at the same time as smoke models are evaluated, and that such field data collection efforts must be done at scales and fuel loadings that approximate real-world fire conditions (Ottmar 11-2-1-11).

The RxCADRE project (Ottmar 11-2-1-11) was a very important step in the progress of the JFSP Smoke Science Plan, although this project was originated as a fire behavior experiment rather than a smoke experiment. In RxCADRE, field experiments were developed to address a need for integrated, quality-assured fuels, fire, and atmospheric data for development and evaluation of fuels, fire behavior, smoke, and fire effects models. The lack of co-located, multi-scale measurements of pre-fire fuels, active fire processes, and post-fire effects data has, as stated earlier, hindered the ability to tackle fundamental fire science questions. RxCADRE enabled scientists to develop processes for collecting complementary research data across fire-related disciplines before, during, and after the active burning periods of prescribed fires with the goal of developing synergies between fuels, fuel consumption, fire behavior, smoke management, and fire effects measurements for fire model development and evaluation. While RxCADRE did not have as a focus the collection of data for evaluation of smoke models and addressed a number of fire science questions, the experiments were not sufficient for comprehensive smoke model validation. To successfully validate and improve smoke and air quality models, longer-term intense burns in complex and heavy fuels will be required, and hence the field experiments will need to be in different fuels and of a larger scale than RxCADRE. Having been opportunistic and building upon the RxCADRE experience, JFSP commissioned a workshop to develop a national plan for fire and smoke model validation (Brown 13-S-01-01).

Model Validation Vision

A wide variety of models are used to project and analyze smoke and its impacts on people and resources. Some models and supporting data are incorporated into such application systems as BlueSky (see: http://www.airfire.org/) and WRAP tools (see: https://www.wraptools.org/) that organize and aid in their applications. However, demonstrating and quantifying model skills for general fire applications remains elusive. Uncertainties in fire emissions and in fire behavior modeling cascade into uncertainties in plume rise, plume chemistry and smoke dispersion, compounding errors. The single scientific need most identified while developing the Smoke Science Plan was that smoke models, and their modeling systems, need to be validated. Validation of smoke modeling has been, and continues to be, limited by insufficient quantity and quality of data. Indeed, this lack of data limits even the development of new conceptual models. However, this lack of data is not addressable by any one scientific group because of the complexity and diversity of the data needed (Bytnerowicz et al., 2009). In simple terms, the effort needed is large, extremely expensive, and requires ground-based and airborne measurements. Clearly, no single group has the resources or scientific capabilities needed (Lentile et al., 2007a and 2007b). Thus, the objective of this theme is to develop the vision and to identify potential partnerships needed to accomplish such a large undertaking.

To begin developing a smoke model validation national plan and the associated partnerships needed, a two-day smoke validation workshop funded by JFSP (13-S-01-01) was held 17-18 September 2013 at the Desert Research Institute (Reno, NV) to formalize the research elements and strategies needed to advance smoke modeling. Participants represented federal, university and international organizations. Several of the participants worked with RxCADRE. Workshop participant expertise included fuels characterization, consumption, combustion, air quality, field experiments, remote sensing, fire behavior, smoke chemistry, dispersion modeling, and atmospheric measurements. This workshop has become the foundation of the in the initiation of the Fire and Smoke Model Evaluation Experiment (FASMEE) in 2016 (Watts et al., 2016). Table 4 presents a brief synopsis of the data needs identified by the Fire and Smoke Model Validation Workshop (JFSP 13-S-01-01), data needs that will guide the FASMEE field work.

Table 4: Example Partial List of Data Needs for Smoke Model Validation (Source: JFSP Smoke Model Validation Workshop Final Report, Brown et al., 2016)

Surface Meteorology	Upper-air Meteor-ology	Fuel Character-istics	Fire Behavior	Ground-based smoke chemis-try	Airplane based smoke chemistry	Satellite Fire Measure-ments	Satellite Smoke Measurements
Air Temp	Air Temp., Humidity, Wind Speed and Dir, Press	Live and dead shrub mass	Wind speed and direction	CO_2, CO	CO2, CO, CH4, H2O	Fire Location	Aerosol Index/optical depth/absorption/effective radius/fine mode fraction/type/angstrom component/scattering albedo
Humidity	Air Temp, Humidity	Live and dead non-woody mass	Fire Radiant Emissive Power	NMOC	Non-methane Organic Compounds (NMOC)	Fire Temperature	Carbon Monoxide
Wind Speed	WS, WD, Turbulence statistics	Fine fuel mass	Fire radiosity	NO_X	NOx (NO, NO2) and NOy	Fire Area	Carbon Dioxide
Wind Dir	WS, WD, Turbulence, plume dispersion, Backscatter intensity	Large woody mass	Fire power	HCN, CH_3CN	O3	Fire Radiative Power	Methane
Solar Radiation	WS, WD, T	Litter depth and mass	Air tempera-ture	$PM_{2.5}$, PM10	HCN, CH3CN	Burned Area	Nitrogen Oxides
Soil Heat Flux		Duff depth and mass	Air flow	Aerosol speciation (OC, EC, black carbon)	Integrated light scattering	Burn Severity	Formaldehyde
3-D wind, turbulence, sonic temperature		Mineral soil exposure	Fire imagery		Actinic flux	Near-source Plume Height	Ozone

The ultimate objective of the Smoke Science Plan was not to collect data and conduct all the research needed to validate smoke models. Rather it was to develop further the information needed that would allow creation of a plan and partnerships whereby such a model validation program could begin. As a first steps we brought together all the research which JFSP had funded before the plan was initiated that related to model validation and reviewed what we had learned, or would learn as projects concluded. We then commissioned a workshop to develop a plan and partnerships to conduct future fieldwork. The next phase is to fully implement the plan, which will result in projects beyond the completion of the Smoke Science Plan under the guidance of FASMEE.

How is This Theme's Information Being Used?

- Work on superfog has resulted in new warning approaches being trialed in the Southern United States.
- Information from project 09-1-4-02 has resulted in changes in the BlueSky modeling system.
- RxCadre has become the 'Rosetta Stone' for developing fire and smoke model evaluations at meaningful scales.
- Agencies such as EPA and NOAA are much more aware of the need to gather fuels and fire behavior information during smoke field campaigns, which is improving cooperation and resource sharing.

Remaining Challenges

Validation of models, and especially such a complex and challenging linkage of models needed to model smoke from wildland fires to distant receptors, is practically impossible. The FASMEE project will not be able to answer all questions, but it is very likely to advance confidence about when models work, don't work, and which are best to apply in which situations. The objectivity that a large, well-managed field data collection program for fire and smoke model validation will give will do much to help lower apprehension about smoke impacts. It will make communication about fire smoke hazards to the public more acceptable as the projections made will be based on a solid foundation of objective data.

However, the biggest immediate challenges are not in smoke dispersion simulation but rather in fire behavior and fuel consumption modeling at scales needed to produce both correct smoke emissions and atmospheric parameters needed for correct plume rise. One should also keep in mind that fine scale meteorology projections, especially nighttime drainage flows, are still an area where new science work needs support. So for those who ardently desire validated smoke models, the FASMEE project is the beginning of a new era that will surely result in information that will improve smoke modeling, and smoke management. From the standpoint of the SSP, FASMEE is the next logical paradigm for the JFSP smoke line of work.

SSP THEME III – SMOKE AND POPULATIONS RESEARCH

The SSP objective for the smoke and populations research theme is to develop the science to objectively quantify the impact of wildland fire smoke on populations and fire fighters, elucidate the mechanisms of public smoke acceptance and increase understanding of the balance between ecosystem health and acceptable smoke exposure risks. In recent years it has become clear that smoke from fires, especially from "megafires", can impact not only the wildland urban interface but also large urban areas some distance removed from the fire itself (Navarro et al., 2016). With more people exposed to wildland fire smoke comes the need to better understand how smoke affects human health, the levels of smoke that create different public health concerns, and how we can best warn the public when smoke events are imminent. Also, as fires become more frequent and larger, and the demands on firefighting resources increase, there is a need to understand the effects of extended exposure for firefighter health. The Smoke Science Plan envisioned research to develop an improved science foundation for assessing health risks from smoke and understanding people's perception of the balance between smoke exposure risk and ecosystem health. Research topics included:

1. The health effects of high concentrations of smoke on individuals, especially to identify "evacuation-levels" of exposure (including fire fighter smoke exposure implications).
2. The public perception and acceptability of smoke at high concentrations for extended durations.
3. Research into the best means for communication about smoke to the public and generating and distributing smoke information, especially smoke hazards, among responsible agencies.
4. Advancing understanding of how to incorporate smoke events in large urban centers into air quality forecasting (such as is now being undertaken by NOAA and EPA).
5. Deepen understanding of public perceptions of the dangers from smoke and improved scientific basis for public health smoke warnings during large fire events.

Since inception of the SSP, ten projects were funded to address these questions. Four have been completed and six remain active as of April 2017. The specific projects are listed in Table 5. Completed projects have addressed public perceptions and tolerance for wildland fire smoke, and the relationship between visibility and fine particulate health standards. These research results are contributing to new public service messaging related to wildland fire smoke and the development of tools that predict smoke impacts on public health and safety. Six projects remain active that are addressing: short-term health impacts of smoke on fire workers and the impacts of ambient smoke concentrations on public health; the toxicology and mutagenicity of smoke constituents; and prototype smoke hazard warning systems. Final outcomes of this theme's research are anticipated to inform smoke hazard warning systems for public health and safety, as well as smoke risk exposure for wildland fire workers.

Table 5: JFSP projects funded that address smoke and populations. Details of projects including final reports can be accessed through the JFSP website: https://www.firescience.gov/index.cfm

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Smoke and Populations Theme	Status
Examining the Influence of Communication Programs and Partnerships on Perceptions of Smoke Management	Troy Hall 10-1-3-02	• Two strongest predictors of public tolerance of smoke form wildland fire are being aware of prescribed fire's benefits and trust in fire managers • Although the public is generally tolerant of wildland fire smoke, it can be a significant concern for those who have had negative health experiences from smoke. • There is room for improving communication with the public about smoke management issues, specifically providing advanced warning about potential smoke impacts and issues.	Completed
Public Perceptions of Smoke: Contrasting Tolerance Amongst WUI and Urban Communities in the Interior West and the SE US	Eric Toman 10-1-3-07	• Informational messages to the public influence smoke acceptance and increase their ability to control their exposure to smoke. • Recommended enhancing interagency coordination in communication efforts to develop clear, unified and consistent messages.	Completed
Public Perception of Smoke and Agency Communication: A Longitudinal Analysis	Christine Olsen 12-3-01-21 (GRIN)	• Perceptions about agencies and smoke remained similar before and after a year of moderate fire activity that included an escaped prescribed fire near the Shasta-Trinity NF in California. Perceived risk associated with smoke increased slightly and was confined to recreation-related impacts. • Most people accept wildland fire smoke and this acceptance is resilient to smoke events. Continuing to promote messages of beneficial fire is a positive course of action for management agencies. • A third of respondents in this study do not accept smoke and most of the reasons were health related. Understanding the background of people who object to smoke can help in the development of smoke management strategies and communication and outreach messages that best address their concerns.	Completed
Wildland Fire Smoke Health Effects on Wildland Fire Fighters & Public	Joe Domitrovich 13-1-02-14	• *Update and existing database of literature related to human health and air pollution specifically related to wildland fire smoke toxicity.* • *Develop a set of risk-based exposure criteria that are specific to wildland fire smoke*.	Ongoing
Visual Range and Particulate Matter Data Analysis and Literature Review	Bill Malm 13-C-01-01	• There are five uncertainties that affect estimation of visual range and associated particulate matter (PM) levels that when added together could make PM estimates off by a factor of 2. • Visual range/particulate concentration relationships could be improved by including location and a measure of relative humidity. • A smartphone application could be developed to directly measure landscape feature contrast, allowing calculation of visual range and therefore more accurate assessment of particulate concentration.	Completed

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Smoke and Populations Theme	Status
Health Effects from Wildfire Air Pollution: a Spatiotemporal Modeling Approach	Michael Jerrett 14-1-04-5	*Preliminary Findings* • *Created fine particulate ($PM_{2.5}$) prediction models that are highly accurate within a single region, but do not extrapolate well to non-overlapping regions.* • *After evaluating nine machine learning prediction algorithms for predicting ozone concentrations, two models, the randomized forest and generalized boosting models, provided predictions of ozone concentration related to wildfires.*	Ongoing
Estimating Fire Smoke Related Health Burden and Novel Tools to Manage Impacts on Urban Populations	Brian Reich 14-1-04-9	• *Distinguish between smoke and non-smoke related exposures in air quality and heath risks in epidemiological studies and conduct a systematic review and meta-analysis of epidemiological risk estimates to evaluate the risk of smoke exposure for all relevant health outcomes.* • *Utilize the BenMAP-CE air pollution tool to characterize the health and economic value of the burden of fire smoke. Use peat fires in rural NC, and the 2013 fire near Sydney, Australia as case studies.* • *Combine model based predicted smoke exposure with health and economic assessment tools to provide real-time forecasts of health risk over space and time.*	Ongoing
The Role of Composition and Particle Size on the Toxicity of Wildfire Emissions	Ian Gilmour 14-1-04-16	*Preliminary Findings* • *Developed novel combustion and smoke-collection system featuring an automated tube furnace to control combustion phases (smoldering/flaming) and a multi-stage cryo-trap system to efficiently collect PM and semi-volatile phases of smoke emissions.* • *Combusted five different fuels (flaming and smoldering phases) to represent contrasting fuel types, and assessed resulting PM for lung toxicity in mice and for mutagenicity in Salmonella bacteria.* • *Determined biological outcomes in two ways: (1) as a potency expressed as toxicity per mass of PM, which is a unit used for regulatory decision-making, and (2) as an emission factor (EF) expressed as toxicity per mass of fuel burned, which is a unit used to express real-world exposures.* • *Lung toxicity and mutagenic potencies of flaming emissions from biomass fuels were found to be greater than those of smoldering emissions (on a mass basis), whereas these toxicological endpoints resulted in greater responses for smoldering than flaming conditions on an EF basis.* • *Eucalyptus and pine smoke emissions induced higher, but not statistically significant, toxicological outcomes compared to other biomass fuel emissions, suggesting that forests composed largely of eucalyptus and pine produced emissions that could cause greater health effects than comparable fires from forests composed of the other types of biomass fuels.* • *Comparison of the mutagenicity data with published data for various combustion emissions indicated that the mutagenicity of smoldering biomass emissions (on an EF basis) was greater than that of traffic emissions.*	Ongoing

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Smoke and Populations Theme	Status
AIRPACT – Fire Enhanced Communication of Human Health Risk with Improved Wildfire Smoke Modeling	Joseph Vaughn 15-1-02-2	*Preliminary Findings* • *Coupled atmosphere and fire behavior modeling experiments performed using WRF-SFire to model the Cougar Creek Fire (WA, 2015) show a significant sensitivity to initial fuel moisture conditions.* • *Because of WRF-SFire's sensitivity to initial fuel moisture, a product that can provide regularly updated estimates of 1 hr, 10 hr, 100 hr, and live fuel moisture classes at fire-model resolutions of ~30m would help model application.*	Ongoing
US Smoke Hazard Warning System: Prototype and Enhancements to Operational Systems	Sim Larkin 15-1-02-4	• *Gather many complex datasets related to fire, smoke and air quality into a central repository for aggregation and distillation into meaningful formats and messages for a variety of end users.* • *Create a Use Needs Group to guide the messaging and products and an Interagency Advisory Board to create a collective vision for moving US Smoke Hazard Warning System forward.* • *Enhance existing operational outlets of air quality hazard information (e.g. EPAs AirNow Smoke Page) to form initial outlet for the Smoke Hazard Warning System.* • *Create a smartphone app that includes a visual range assessment tool.*	Ongoing

Smoke and Populations

When the Smoke Science Plan was written, there was very little information in the scientific literature specific to the health effects of wildland fire on the general population. Few if any epidemiological studies had been conducted. Most of the available information on health effects was focused in the acute effects of smoke to firefighters. And no studies had been conducted to understand the social science behind public acceptance and tolerance of wildland fire smoke. Given the increasing occurrence and impacts of wildland fire on a greater portion of the public, time was ripe to initiate research in these areas.

A lot has been accomplished in a relatively short period of time and it is amazing how much new information is available related to this theme since the beginning of the SSP. This is especially apparent when reviewing the agendas for the first and second International Smoke Symposia held in 2013 and 2016. In 2013 there were 18 presentations focused on research into public perception and acceptance of wildland fire smoke, health effects to wildland firefighters, and revision of the 2008 Wildfire Smoke Guide for Public Health Officials. In 2016 there were 39 presentations; 18 on communicating smoke impacts, 11 on health effects of smoke exposure, and 10 on smoke forecasting and hazard warning.

The presentations and discussions at the Second International Smoke Symposium (ISS2), held in November 2016, demonstrated that the smoke and populations issues identified in the SSP continue to be valid. And JFSP is not the only entity funding research in this area. New information is showing that wildfire seasons are longer and hotter, wildfire intensity is increasing, smoke impacts to the public are longer and at higher levels, and medical facilities are seeing increased health impacts from smoke. In just the past three years there has been an impressive addition to the literature available on health effects. Recent systematic reviews have shown positive associations between smoke exposure and health outcomes in 70% of all mortality studies, and in 90% of all respiratory health outcome studies (Liu et al., 2015, Reid et al., 2016a). Asthma, COPD, bronchitis and pneumonia can all be caused by wildfire smoke. Four large epidemiological studies on health outcomes associated specifically with wildfire smoke have been published since 2014 (Johnston et al., 2016; Heikerwal et al., 2015; Reid et al., 2016b; Tinling et al., 2016). There is also a new review of the health effects of wildland fire smoke on wildland firefighters showing decreased lung function across workshifts and possible cumulative effects across seasons (Adetona et al., 2016). Kathleen Navarro presented work on characterization of PAH exposure in firefighters and showed that nightshift work, and those firing and holding had the highest exposures. Michael Williams-Bell studied impacts of smoke on acute cognitive performance in wildland firefighters and found little effect. All areas of health effects research recognized the need for longer-term exposure studies.

VISIBILITY AND FINE PARTICULATE HEALTH STANDARDS

This research identified five uncertainties that affect estimation of visual range and associated particulate matter (PM) levels that when added together could make PM estimates off by a factor of 2. It was also found that visual range/particulate concentration relationships could be improved by including location and a measure of relative humidity.

Several presentations showed that increasingly public health messaging is created through collaborative networks that include all key players. And new technology is being embraced. Mobile devices can be used to collect data from individuals as well as broadcast individualized information on smoke exposure (ISS2 presentation " AirRater-A mobile application for public air quality alerts and symptom reporting." Grant Williamson and Chris Lucani). Low cost portable air quality sensors that report air quality in increments as short as one minute are becoming more available. The challenge has been in how to interpret the data. EPA published guidelines on interpreting and communicating short-term air sensor data late in 2016 (Keating et al., 2016). Social media is being employed to get the word out on when and where smoke events can be expected, and to provide protective measures that can be taken by the public. Smoke blogs developed cooperatively between state and federal agencies in California, Idaho, Oregon and Washington are used to keep the public informed and involved during wildland fire events.

The next sections will show how JFSP funded research is contributing to the body of knowledge that is developing on wildland fire smoke and populations.

JFSP Science on Public Perception and Tolerance for Smoke

The projects funded by JFSP represent the only existing social science research on wildland fire smoke for the US. All of the work has been done since 2010 through cooperative efforts between Oregon State University, Ohio State University and the University of Idaho.

Public Perceptions of Smoke: Contrasting Tolerance Amongst WUI and urban Communities in the Interior West and SE US (Toman 10-1-3-07). This research confirmed that informational messages to the public influence smoke acceptance and increase their ability to control their exposure to smoke. The effectiveness of messages is increased when the background of the audience, including the types of forests they are familiar with and past experience with fire, is aligned with the communication goals. Researchers recommended enhancing interagency coordination in communication efforts to develop clear, unified and consistent messages. This is foundational for those developing public health messaging related to wildland fire smoke events and appears to have been adopted by the fire, air quality and public health communities, as evidenced by the number of cooperative efforts that have sprung up since the 2013 ISS.

Public Perceptions of Smoke and Agency Communication: A Longitudinal Analysis (Olsen 12-3-01-21). This GRIN study expanded on the Toman project by conducting a follow-up to the original work to see how public opinions changed after a year with moderate fire activity. The perception of risk and agency confidence declined slightly, but there was no change in the agency trust level. And interestingly, smoke acceptance ratings did not change. Apparently most people accept wildland fire smoke and this acceptance is resilient to smoke events.

Examining the Influence of Communication Programs and Partnerships on Perceptions of Smoke Management (Hall 10-1-3-02). Researchers found that the two strongest predictors of public tolerance for smoke from wildland fires are: 1) being aware of prescribed fire’s benefits, and 2) trust in public fire managers. Although the public is tolerant of wildland fire smoke, it can be a significant concern for those who have had negative health experiences from smoke. They also found that there is room for improving communications with the public about smoke management issues, specifically providing advanced warning about potential smoke impacts and issues.

JFSP Science on the Relationship Between Visibility and Fine Particulate Health Standards

This work was the direct result of a request to JFSP by the National Wildfire Coordinating Group's Smoke Committee (SmoC). Several states had adopted techniques using the visual appearance of smoke to estimate fine particulate concentrations in smoke where monitoring data was not available. This information is then used to guide public health messages. SmoC was aware of the possibility of considerable uncertainty in particulate estimates made from visual estimates and requested an assessment by experts in the field of visibility.

Visual Range and Particulate Matter Data Analysis and Literature Review (Malm 13-C-01-01). This research identified five uncertainties that affect estimation of visual range and associated particulate matter (PM) levels that when added together could make PM estimates off by a factor of 2. It was also found that visual range/particulate concentration relationships could be improved by including location and a measure of relative humidity. Finally, the research proposed that a smartphone application could be developed to directly measure landscape feature contrast, allowing calculation of visual range and therefore more accurate assessment of particulate concentration. Bill Malm presented these results at the 2013 International Smoke Symposium.

Based on recommendations from this project, new behavior-based guidance was developed for using visual range to assess smoke levels in the interior western US and incorporated into the 2016 revision of Wildfire Smoke: A Guide for Public Health Officials (https://www3.epa.gov/airnow/wildfire_may2016.pdf). Also, a smartphone application for estimating particulate concentration is currently under development as part of the Larkin project (15-1-02-4).

JFSP Science on the Health Impacts of Smoke on Fire Workers and the Public

All of these projects are ongoing and have few preliminary findings to share at this time. The project led by Gilmour is closer to completion that the others and is providing new information on the toxicity and mutagenicity of wildland fire emissions. The findings are prompting EPA to undertake further research to assess effects of fire emissions on human health. They are also interested in investigating the health effects of aged wildland smoke mixed with urban air pollution.

Wildland Fire Smoke Health effects on Wildland Fire Fighters and the Public (Domitrovich 13-1-02-14). Acute exposure of firefighters to wildland fire smoke is one area that had seen considerable research prior to the SSP. The focus of this active project is to update an existing database of literature related to human health and air pollution, specifically related to wildland fire smoke toxicity, and to develop a set of risk-based exposure criteria.

The Role of Composition and Particle Size on the Toxicity of Wildfire Emissions (Gilmour 14-1-04-16). This project is the first of its kind to investigate the variation in toxicity of smoke emissions resulting from various fuel types, combustion conditions, and particle sizes and chemistry. The relative cardiopulmonary toxicity and mutagenicity of coarse and fine fire emissions were compared over four distinct fuel types obtained from both smoldering and active flame phases. Results were presented in 2016 at both the Second International Smoke Symposium and the Fifth International Fire Behavior and Fuels Conference. Fuel types and combustion phases were found to dramatically alter the emission characteristics, mutagenicity and lung toxicity of wildland fire smoke. And although mutagenicity and toxicity of particulate were greater in smoke from flaming combustion on an equal mass basis, when adjusted for emitted particulate mass, mutagenicity and toxicity of smoke were greater in the smoldering phase. This JFSP-funded project has stimulated additional interest and research. EPA is currently conducting follow-up work to assess pulmonary function and toxicity, neurobehavioral changes, cardiovascular function and toxicity from acute and sub-chronic inhalation exposure of smoke. EPA is also interested in investigating the effects of aged wildland smoke mixed with urban air pollution.

Health Effects from Wildfire Air Pollution: A Spatiotemporal Modeling Approach (Jerrett 14-1-04-5). This is an active project that is developing spatiotemporal estimates of population exposure to fine particulate matter and ozone from the 2008 northern California fires using statistical models. They will estimate the effect of wildfire ozone and fine particulate on cardiorespiratory hospitalizations, emergency department visits, and mortality. They also plan to identify vulnerable populations for wildfire smoke to assist public health agencies in targeting messages and interventions during wildland fire events.

Estimating Fire Smoke Related Health Burden and Novel Tools to Manage Impacts on Urban Populations (Reich 14-1-04-9). This is an active project that will distinguish between smoke and non-smoke related exposures in air quality and health risks in epidemiological studies and conduct a systematic review and meta-analysis of epidemiological risk estimates to evaluate the risk of smoke exposure for all relevant health outcomes. They will utilize the BenMAP-CE air pollution tool to characterize the health and economic value of the burden of fire smoke. They are using peat fires in rural NC and the 2013 fire near Sydney, Australia as case studies. The will combine model based predicted smoke exposure with health and economic assessment tools to provide real-time forecasts of health risk over space and time. At ISS2 Anna Rappold reported for this project on the public health burden of smoke in the US. They are examining the scope and magnitude of wildfire related premature deaths and illnesses between 2008-2012, and estimating the economic value of these impacts. This is the first attempt to quantify the human health burden across the continental US across multiple years. They show that effects vary from year to year, but wildland fires pose a significant burden to public health on an annual basis. The states most affected were CA, ID, OR, LA and GA. These areas saw repeated wildland fire events that were responsible for the greatest levels of PM over the 5-year period.

JFSP Science Toward Developing a Prototype Smoke Hazard Warning System

AIRPACT-Fire Enhanced Communication of Human Health Risk with Improved Wildfire Smoke Modeling (Vaughn 15-1-02-2). This is an active project that is developing AIRPACT-FIRE to deliver enhanced wildfire related air quality forecast and 'nowcast' information to the Pacific Northwest Region and for eventual use in the hazard warning system under development by Larkin, JFSP Project 15-1-02-4.

US Smoke Hazard Warning System: Prototype and Enhancements to Operational Systems (Larkin 15-1-02-4). This is an active project the is gathering many complex datasets related to fire, smoke and air quality into a central repository for aggregation and distillation into meaningful formats and messages for a variety of end users. Some advances made to date include development of FireTracker, a system to better estimate fire activity information; BlueSky4, a new, entirely reworked system that will more easily embed in other models providing needed flexibility for an operational system; and updating of emissions factors. This project has created a broad collaboration to guide the messaging and products, and to create a collective vision for moving a US Smoke Hazard Warning System forward. The group includes the National Weather Service, NOAA, NASA Health and Air Quality Applied Sciences Team, US EPA, CDC, Desert Research Institute, Sonoma Tech, University of Washington, US Forest Service, and the National Park Service. The initial operational outlet for the Smoke Hazard Warning System is EPA's existing website, AirNow (https://airnow.gov/index.cfm?action=topics.smoke_wildfires). They are also working to develop a smartphone application that includes a visual range assessment tool based on recommendations provided by JFSP project 13-C-01-01.

How is This Theme's Information Being Used?

- EPA has enhanced the AirNow website (designed to provide the public with current and forecasted air quality and health advisories) to include wildland fire and smoke information. This website is becoming a primary portal for the public to obtain current wildfire information and smoke advisories. (https://airnow.gov/index.cfm?action=topics.smoke_wildfires)
- *Wildfire Smoke: A Guide for Public Health Officials* was revised and field-tested in 2016 (https://www3.epa.gov/airnow/wildfire_may2016.pdf.). This guidance document is the result of cooperative efforts between USEPA, the US Forest Service, US Center for Disease Control and Prevention, and the California Air Resources Board. The revision includes new tools for assessing the location and level of smoke exposure, and strategies to reduce smoke exposure by the public.
- *Wildland Fire Personnel Smoke Exposure Guidebook (version 3-1- 2016) - DRAFT* was produced by the NWCG SmoC Training Subcommittee and the University of Idaho. Although it is a Draft document, it is posted for use and states that it will be updated as new information becomes available. https://www.frames.gov/documents/smoke/Smoke-Exposure-Guidebook_NWCG-SmoC-UI_20160301-draft.pdf

- The Wildland Fire Air Quality Response Program (led by the US Forest Service in partnership with other agencies such as the National Park Service) is one group that will use all of the information created by JFSP under this theme. This Program was created to directly assess, communicate and address risks posed by wildland fire smoke to the public as well as fire personnel. It depends on four primary components: specially trained personnel called Air Resource Advisors (ARA), air quality monitoring, smoke concentration and dispersion modeling, and coordination and cooperation with agency partners. Air Resource Advisors are technical specialists trained to work on wildland fire smoke issues. They are dispatched to fire incidents to assist with understanding and predicating smoke impacts on fire personnel and the public. They analyze, summarize and communicate smoke impacts to incident teams, air quality regulators and the public.

Remaining Challenges

Recent wildfire seasons are longer and hotter and the smoke impacts to the public are longer and at higher levels, and all of the modeling studies how that this will persist into the future. The single most discussed challenge at the 2016 International Smoke Symposium (for this theme) was the need to improve our understanding of the health effects of long-term and repeated exposure to wildland fire smoke by both firefighters and the public. There is also need for a better understanding of the health effects of wildland fire smoke alone and mixed with urban pollution. Controlled human exposure studies are needed to understand how inhalation of wood smoke affects systems. EPA is embracing this by expanding the toxicology work they began with JFSP funding into a health risk assessment from inhalation exposure to wildland fire smoke. They would eventually like to look at the health effects of the wildland smoke/urban pollution mixture. This area of research, which is primarily concerned with human health response to smoke, may best be pursued by agencies like EPA, CDC and the National Institutes of Health rather than JFSP.

There is great interest in the pubic health and fire management communities to effectively communicate health impacts from smoke exposure to the public. We are already seeing an interdisciplinary response to this in terms of developing smoke hazard warning systems that incorporate public health messages. The future would ideally include forecasted public health impacts given forecasted smoke exposures. Clearly, public health officials see this a more direct way to encourage actions to reduce exposure in “at risk” individuals. And social scientists would be able to evaluate how access to forecasts of public health impacts would influence risk perception and exposure mitigation decisions by the public. Communicating potential impacts of wildland fire smoke, and accessing the effectiveness of these messages on public perception and risk mitigation are areas of where continued support by JFSP may be needed (in the opinion of the smoke science advisors).

Providing individuals with tools to make health related decisions during smoke events is a growing area of interest in the public health community. Portable air sensors are becoming more available to a broader sector of the public and the challenge is in educating people on how to best use this information. EPA is making advances in interpreting short-term air monitoring data, but given the rapid pace of technology development, we can assume that challenges may continue. There may also be a role for JFSP supported research (perhaps in cooperation with NIOSH) into how to best use these personal portable air sensors to evaluate and ensure wildland firefighter health and safety.

Public health officials and smoke managers recognize that there is a need for consistent evidence-based health risk reduction measures that can be recommended to the public. Once such measure is the personal air cleaner. Personal air cleaners (PCA) have been shown to be effective in reducing exposure during some smoke events (Barn et al. 2016). More details are needed on exactly how to best use PCAs to reduce smoke exposure and improve health outcomes under varying smoke intensities. JFSP may want to take a cooperative role in funding this work.

Many aspects of smoke dispersion forecasting have improved greatly in recent years and this makes development of smoke hazard forecasting possible. However, there continue to be challenges and a critical element for real-time fire predictions remains elusive; fire activity information. Modelers are always in need of better real-time fire activity data. This includes fire location, acres burned, fuel type and fuel consumption, and fire growth. Satellite data is essential to real-time forecasting, but ground reports would improve the estimates. Temporal allocation of emission by hour of the day, dynamic description of fuel characteristics (such as moisture content) and fuel availability are also challenging. These are areas where we (smoke science advisors) could see a continuing need for research support by JFSP.

SSP THEME IV– CLIMATE CHANGE AND SMOKE RESEARCH

The objective for the climate change and smoke research theme is to develop an understanding of the implications of wildfire smoke to and from climate change using IPCC scenarios as guidelines. One of the most important issues facing forest management, and perhaps still one somewhat controversial, is climate change. But the global climate is changing and the change is increasingly well documented. According to NOAA's National Climate Center "In 2016, the contiguous United States (CONUS) average temperature was 54.9°F, 2.9°F above the 20th century average. This was the second warmest year for the CONUS, behind 2012 when the annual average temperature was 55.3°F. This marks the 20th consecutive year that the annual average temperature for the CONUS was above the 20th century average. The last year with a below-average temperature was 1996. Since 1895, the CONUS has observed an average temperature increase of 0.15°F per decade." National Climate Report, 2016 Annual Average. (https://www.ncdc.noaa.gov/sotc/national/201613)

FUTURE CLIMATE AND SMOKE

To determine future fire emissions the SSP proposed use of new IPCC scenarios that include high, medium, and low radiative forcing to guide research (http://www.ipcc.ch/popup_scenarios.htm). From these forcing scenarios, which are a direct result of projected shifts in atmospheric gas concentrations with forcings calculated from the radiative trapping coefficients of the gases, IPCC modeled future climates.

Recent research has addressed relationships between climate and fire (Balshi et al., 2008; Brown et al. 2004; Dennison et al., 2014; Flannigan et al., 2009; Spracklin et al., 2009; Westerling et al., 2006; Williams et al., 2005; Yue et al., 2013; Zhang et al., 2010). Data indicate that total burned area in the US has been increasing over the past few decades although there remains considerable inter-annual variation (http://www.nifc.gov/). On a national basis, it is difficult to discern any climate change pattern because there is strong regional variability. Relationships between the global climate and regional climates are very complex and highly non-linear. As a result trying to determine how the changing global climate might affect fire and resultant air quality in the United States is a challenging multistep process. It involves a cascade of different simulation models. Firstly it requires models of the changing global climate and models capable of downscaling their results to simulate regional and sub-regional scale climates. Secondly, models capable of simulating ecological responses to the changing climate are needed. Thirdly, models able to simulate the effects of the altered ecology and climate on forests, and, especially on fuel buildup and fire regimes, are needed. Then finally, models to simulate fire occurrence, fuel consumption and smoke production are required. Because there are so many different models involved and models that in some cases are built upon completely different intellectual constructs and utilize different data in different ways, results may be vastly different and quite uncertain. In order to make progress on such a complex issue we felt it appropriate to utilize, to the extent possible, the efforts of the very large and significant climate research community. For this reason, we suggested use of IPCC (Intergovernmental Panel on Climate Change, the UN scientific consensus forum) climate scenarios. In this way, any results from this research will be relevant to the broader climate change community. There have been efforts in the past to simulate the future, for example Spracklen et al. (2009) projected a 54% increase by the 2050s for annual mean area burned in the western U.S., near doubling of wildfire carbonaceous aerosol emissions, increasing summertime organic carbon aerosol concentrations by 40% and elemental carbon concentrations by 20% based on a GCM climate projection and chemical model simulation. Other studies have projected similar dramatic results. However, most of these studies have been based on different assumptions and have significant limitations. In the SSP we are seeking to link future studies closely with the international climate change research community. For many years, the climate change research community has been developing scenarios of the future to estimate data required to drive climate simulation models (http://www.ipcc.ch/popup_scenarios.htm). The ecological research community uses these simulated future climates to project future ecosystems. Current speculation is that many forest ecosystems are likely to experience increased stress, including increased flammability, as a result of a drier, hotter climate (Brown et al., 2004; Flannigan et al., 2009; Westerling et al., 2006). The Smoke Science Plan recommended that JFSP fund studies to assess fire and smoke consequences of simulated future climate and its altered ecology. Recognizing that the JFSP has limited resources to address this large scientific area, we recommended collaboration with the climate change science community by using contemporary IPCC climate scenarios to ensure that work done by the JFSP is relevant to other research being done nationally by the US Global Change research program (http://www.globalchange.gov/) and internationally.

To determine future fire emissions the SSP proposed use of IPCC scenarios that include high, medium, and low radiative forcing to guide research (http://www.ipcc.ch/popup_scenarios.htm). From these forcing scenarios, which are a direct result of projected shifts in atmospheric gas concentrations with forcings calculated from the radiative trapping coefficients of the gases, IPCC modeled future climates. Using these, the SSP recommended that JFSP research US fire smoke consequences of the projected climate and ecosystems resulting from each of the three scenarios. Inherent to the process researchers were encouraged to employ assemblages of models and not just one specific model or modeling system in hope to achieve a better sense of both certainties and uncertainties in the simulated climates and smoke outcomes. This work focuses research on climate change event drivers of large-scale fire (multi-week burn durations) and smoke emissions (100-1000km) and the climate system implications of increased smoke emissions and their long-range transport (continental to global scales). By using the IPCC scenarios, JFSP research for climate change and smoke will naturally harmonize with the large international body of research. This approach is technically and scientifically feasible, yet challenging. If done properly it will potentially go beyond merely acknowledging that emissions may increase and provide a quantitative foundation and context for work beyond the SSP scope.

The original SSP suggested a variety of specific research projects some of which were implemented, some not and some projects were shifted from the smoke and populations theme to this theme because SSP advisors felt they fit here better.

Specific research projects that the SSP funded under the Climate Change and Smoke Theme addressed three components of the general issue; black carbon related issues; potential megafire impacts on megacities, and; projected future climate change impacts on smoke and smoke impacts on climate.

Under the black carbon issue, studies included: (1) an assessment of the potential for smoke from US fires to reach the artic (this was an earlier funded study that was linked to this theme), (2) measurements of optical properties and climate impacts of aerosols (black and brown carbon) from wild and prescribed fires in the US (this was an earlier funded study that was linked to this theme), and (3) modeling the contributions of fire on black carbon atmospheric concentrations and deposition (this was an earlier funded study that was linked to this theme).

Two research projects assessed the impacts of Megafires on US population centers (originally funded under the Smoke and People Theme but fits better here).

Finally research activities in projecting future climate impacts included a review paper to outline smoke consequences of IPCC's Scenarios of future climate and ecosystem changes, a second review paper to outline the impact of future fires on greenhouse gas and their potential for changing the climate and two modeling studies assessing the impact of projected climate and ecosystem changes resulting from the IPCC's scenarios on smoke and air quality in the US regionally and nationally.

Table 6: JFSP projects funded that address climate change and smoke. Details of projects including final reports can be accessed through the JFSP website: https://www.firescience.gov/index.cfm

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Smoke and Climate Change Theme	Status
Identification of Necessary Conditions for Arctic Transport of Smoke from US Fires	Sim Larkin 10-S-2-01	• Forward-trajectory analyses simulated air parcel transport from 13, 482 source points within the continental US to the Arctic Circle and showed the potential for transport was highest from the Northeastern US, and most likely during the winter and early spring months. • Although the Southeast has the most prescribed fire emissions, there is relatively low transport potential to the Arctic during the spring burning season. • Web-based tools developed to assist managers interested in mitigating potential Arctic black carbon impacts include daily predictions for Arctic transport potential.	Completed
Measuring the Optical Properties and Climate Impacts of Aerosol from Wild and Prescribed Fires in the US	Sonia Kreidenweis 11-1-5-12	• Aircraft-based measurements from prescribed burns in South Carolina allowed quantification of emissions estimates for 97 trace gases, including precursors to secondary organic aerosols (SOA). • Results refine BC and SOA precursors in emissions inventories, which will allow better assessment of overall impacts of wildland fires on fine particle concentrations. • Observational data showed a large portion of the organic matter in a highly concentrated plume near the source would volatilize and repartition to the gas phase as the plume dilutes, indicating air quality models attempting to represent near-field concentrations of fine particles need to actively treat gas-particle partitioning.	Completed
Modeling Study of the Contribution of Fire Emissions on Black Carbon (BC) Concentrations and Deposition Rates	Serena Chung 11-1-5-13	• BC concentrations were significantly elevated by wildland fires in the western US during the 1997 to 2004 study period. • Non-wildland fire sources dominated 2011 annual BC deposition rates to glacial areas in the US, though monthly contributions during summer from wildfires and during fall and winter from prescribed fires can be significant. • Prescribed fires can be significant contributors to BC deposition onto snow-covered surfaces when prescribed burning coincides with snow season.	Completed
Impacts of Mega-Fires on Large US Urban Area Air Quality Under Changing Climate and Fuels	Yong Liu 11-1-7-02	• New model was developed to project mega-fire occurrence that better accounts for extreme weather events associated with such fires. • Number of months with high to extreme fire potential will increase by 1-3 months in the future, and fire potential risk will increase by one grade (e.g. moderate to high) in many regions. • Prescribed burn windows are expected to become shorter in the future in the Eastern US, Pacific coast and Southwest border areas due increased risk of fire escape.	Completed

Title	Principal Investigator / JFSP Project #	• Key Findings or Goals: Smoke and Climate Change Theme	Status
Future Mega-Fires and Smoke Impacts	Sim Larkin 11-1-7-04	• Mega-fire risk during mid-century (2046-2065) is predicted to be greatest in the western US and in limited areas along the east coast and upper Midwest. • Smoke Risk, a measure of how smoke from the source location may impact human populations, is projected to be most heavily concentrated in CA, MN and along the eastern seaboard. • A Smoke Impact Potential metric (SIP) was developed using fire emissions and smoke transport patterns to smoke sensitive areas. Climatological maps of SIP could easily be converted into an assessment tool for regional commands seeking a simple system to rank fires based on smoke impact potential.	Completed
Smoke Consequences of IPCC's Scenarios Projected Climate and Ecosystems Changes in the US - Review Paper	Don McKenzie 12-S-1-02	• Provides background on how to interpret and potentially utilize model results from projects projecting climate-changed future forests, fire regimes, smoke and AQ impacts.	Completed
Estimating the Effects of Changing Climate on Fires and Consequences for US Air Quality Using a Set of Global and Regional Climate Models	Jeffrey Pierce 13-1-01-4	*Preliminary Findings* • *After 2050, fire emissions may be the dominant source of summertime $PM_{2.5}$ in many regions across the US, offsetting benefits of other anthropogenic emission reductions.* • *After 2050, fire emissions may be the dominant source of summertime $PM_{2.5}$ over the eastern U.S., and many states in this region may not attain the EPA National Ambient Air Quality Standard of 12 ug/m3.* • *Demographic changes may be a key factor controlling future fire emissions. Area burned is very sensitive to population density, and future population growth may reinforce or counteract the impact of fire activity due to climate on a regional scale.* • *Simulations showed that future changes in area burned over North America will be more noticeable after 2080 and this led to expanding the scope of the project to the end of the century.* • *In the future, agricultural fires will account for about 5-10% of the total area burned across the US.*	Ongoing

Title	Principal Investigator / JFSP Project #	Key Findings or *Goals*: Smoke and Climate Change Theme	Status
Assessing the Impacts on Smoke, Fire and Air Quality Due to Changes in Climate, Fuel Loads, and Wildfire Activity over the SE United States	Uma Shankar 13-1-01-16	*Preliminary Findings* • *Completed selection of high and low fire years from two representative decades, current (2000 - 2005) and future (2040-2050), using two general circulation model (GCM) results. Future years were simulated with two different Representative Concentration Pathways (RCP 4.5 and RCP 8.5) for greenhouse gas forcing by the end of the century.* • *Completed regional climate modeling for the southeast U.S. for the 12-member ensemble of cases.* • *Methodology developed for fuel load projections using the GCMs' Dynamic Global Vegetation Model outputs in three carbon compartments: leaf, litter and coarse woody debris, relative to the FCCS fuel loads representing the historical period (2005).* • *Completed the baseline (no fuel load change) estimation of daily wildfire emissions to create wildfire emission inventories for the 12 cases. Merged these with anthropogenic emissions for air quality modeling.* • *Estimating sensitivity of wildfire emissions to fuel load changes. Inputs to the BlueSky/CONSUME fire emissions model are being modified to capture changes in spatial variability of fuel loads in the Southeast by mid-century relative to baseline spatial distribution in 2005.* • *Background methodology paper was published on projecting annual area burned into future years. This provided the basis for the daily "area burned" estimates for the fire inventories.*	Ongoing
Potential Climate Feedbacks of Changing Fire Regimes in the US: A Review	Richard Birdsey 16-S-01-2	• The biggest challenge in quantifying the impacts of wildland fire on climate is the lack of high-quality and extensive data streams for fire occurrences and emissions. Fire data on fuel characteristics, burn severity, burn area, fuel consumption and the fire weather, all at appropriate spatial scales, is especially important. • Biomass burning is considered one of the major sources of organic carbon (OC) emissions. OC is likely to cause strong warming effects, not only from its black carbon component but also from other carbon aerosols whose radiative climate impacts are less well quantified in most climate models. • Current estimates show that carbon emissions from all fires in the US are comparable to the net uptake of carbon from the atmosphere by forests in the US; meaning that US forests may not be a net carbon sink when fires are taken into account.	Completed

Black Carbon and Related Issues

In part responding to concerns raised by the National Wildfire Coordinating Council's Smoke Committee (SmoC) the JFSP initiated three projects to address smoke impacts and climate change prior to implementing the SSP.

One project, *Identification of Necessary Conditions for Arctic Transport of Smoke from US Fires* (Larkin 10-S-2-01), identified conditions needed for US fire smoke to transport black carbon to the Artic and calculated forward-trajectories to simulate air parcel transport from 13, 482 source points within the continental US to the Arctic Circle. These showed that the potential for transport was highest from the Northeastern US, and most likely during the winter and early spring months. Although the Southeast has the most prescribed fire emissions, there is relatively low transport potential to the Arctic during the spring burning season. The project developed Web-based tools (http://www.airfire.org/projects/arctic-transport/: http://www.airfire.org/data/arctic-transport-clim/) to assist managers interested in mitigating potential Arctic black carbon impacts by providing daily predictions for Arctic transport potential. This study has produced two publications that are listed in the references.

A second project, *Measuring the Optical Properties and Climate Impacts of Aerosol from Wild and Prescribed Fires in the US* (Kreidenweis 11-1-5-12), collected aircraft-based measurements from prescribed burns in South Carolina that allowed quantification of emissions estimates for 97 different trace gases, including precursors to secondary organic aerosols (SOA). Results refine both BC and SOA precursors in emissions inventories, which will allow better assessment of overall impacts of wildland fires on fine particle concentrations. Observational data showed a large portion of the organic matter in a highly-concentrated plume near the source would volatilize and repartition to the gas phase as the plume dilutes, indicating air quality models attempting to represent near-field concentrations of fine particles need to actively treat gas-particle partitioning. This study has produced a number of publications that are listed in the references.

The third project, *Modeling Study of the Contribution of Fire Emissions on Black Carbon (BC) Concentrations and Deposition Rates* (Chung 11-1-5-13), sought to identify the relative amounts of BC contributed by wildfire and prescribed burning to upland areas in the western US. BC concentrations were significantly elevated by wildland fires in the western US during the 1997 to 2004 study period. Non-wildland fire sources dominated 2011 annual BC deposition rates to glacial areas in the US, however during summer monthly contributions from wildfires and during fall and winter monthly contributions from prescribed fires were significant. Prescribed fires were significant contributors to BC deposition onto snow-covered surfaces when prescribed burning coincides with snow season. This study has produced a number of publications that are listed in the references.

Future Impacts of Megafire

The SSP originally addressed the issue of smoke impacts on people with two projects focused on considering the impacts of potential future megafires on the population centers of the US. Whilst these projects contribute to the Smoke and People theme, we feel that they are perhaps better viewed as part of the Climate Change and Smoke theme.

Impacts of Mega-Fires on Large US Urban Area Air Quality Under Changing Climate and Fuels (Liu 11-1-7-02) developed a new model to project mega-fire occurrence that accounts for extreme weather events associated with such fires. Model results suggest that the number of months with high to extreme fire potential are likely to increase by 1-3 months in the future, and fire potential risk will increase by one grade of the Keetch–Byram Drought Index (KBDI) (Keetch & Byram, 1968) (e.g. moderate to high) in many regions. Further, the model suggests that prescribed burn windows are expected to become shorter in the future in the Eastern US, Pacific coast and Southwest border areas due increased risk of fire escape. This study has produced a number of publications that are listed in the references. An extension of this work, funded by USDA NIFA, was presented at ISS2; *Parameterizing Wildfire Induced Land-surface Changes for Fire-Climate Interaction Modeling* by Liu et al. They assessed land surface property changes caused by large wildland fires in United States. Satellite remote sensing tools including MODIS and Landsat quantitatively evaluated changes in vegetation index (NDVI), leaf area index (LAI), albedo, and day and night temperature from more than 10 large fires. The results indicated that large changes happened for most fires with dense vegetation coverage (NDVI over 0.5 or LAI over 1.0) and substantial changes last 4-10 years. The duration is longer and the changes occur mainly in winter in cool-region fires. Albedo is reduced shortly after fires but then increases, while other properties change consistently throughout the post-fire periods. Based on these results parameterization schemes were developed for earth modeling systems to simulate the long-term local and regional climate responses to wildfires.

Future Mega-Fires and Smoke Impacts (Larkin 11-1-7-04) applied a variety of modeling techniques that suggest mega-fire risk during mid-century (2046-2065) may be greatest in the western US and in limited areas along the east coast and upper Midwest. Smoke Risk, a measure of how smoke from the source location may impact human populations, is projected to be most heavily concentrated in CA, MN and along the eastern seaboard. A Smoke Impact Potential metric (SIP) was developed using fire emissions and smoke transport patterns to smoke sensitive areas. Climatological maps of SIP could easily be converted into an assessment tool for regional managers seeking a simple system to rank fires based on smoke impact potential. This study has produced a number of publications that are listed in the references.

Climate Change Impacts on Smoke

JFSP funded a special project *Smoke Consequences of IPCC's Scenarios Projected Climate and Ecosystems Changes in the US - Review Paper* (McKenzie 12-S-1-02) under the Theme to develop a critical review paper assessing the state of the science of simulating effects of climate change on forest ecosystems, fuels, fire regimes and the resulting smoke (McKenzie et al., 2014.) This paper addresses essential ingredients of a modeling system for projecting smoke consequences in a climate that is expected to change wildfire regimes significantly. Each component of the system is described and suggestions for appropriate ways to simulate elements are made along with providing general guidelines for making choices among potential components. The paper targets an audience of active researchers in the field and neither prescribes nor advocates particular models or software. Instead, it highlights potentially fruitful ways of thinking about the task as a whole and its components, while providing substantial, if not exhaustive, documentation from the primary literature as reference. This paper provides a guide to the complexities of smoke modeling under climate change, and a research agenda for developing a modeling system that is equal to the task while being feasible with current resources.

FUTURE FIRE AND SMOKE IMPACTS ON CLIMATE

Researchers found that both the effects of wildland fire emissions on atmospheric radiative forcing and fire-induced landscape modifications that change earth's surface influence climate. Biomass burning is considered one of the major sources of organic carbon (OC) emissions. OC is likely to cause strong warming effects, not only from its black carbon component but also from other carbon aerosols whose radiative climate impacts are less well quantified in most climate models. Aerosol and related VOC emissions vary considerably across vegetation and fuel types, vegetative state, species composition and with regard to fire intensity.

Assessing the Impacts on Smoke, Fire and Air Quality Due to Changes in Climate, Fuel Loads, and Wildfire Activity over the SE United States (Shankar 13-1-01-16). This project is providing an efficient climate downscaling approach at spatial-temporal scales suited to model fire weather changes in the Southeastern US (SEUS) from 2000-2050. These meteorological inputs will be used to estimate changes in live and dead fuel and daily fire activity from current to future climates in the SEUS, and use the fuel estimates in air quality modeling to bracket likely future fire regimes. Finally, the project will analyze potential air quality impacts of wildfire emissions relative to the national ambient air quality standards in current and future periods. In response to a request for an update on progress under this project, Shankar sent the following: "Completed the selection of high and low fire years from two representative decades, one current (2000 - 2005) and one future (2040-2050), using two general circulation model (GCM) results; future years were simulated with two different Representative Concentration Pathways (RCP 4.5 and RCP 8.5) for greenhouse gas forcing by the end of the century. Completed regional climate modeling for the Southeastern U.S. for the 12-member ensemble of cases developed above. Developed a methodology for fuel load projections using the GCMs' Dynamic Global Vegetation Model outputs in three carbon compartments: leaf, litter and coarse woody debris, relative to the FCCS fuel loads representing the historical period (2005). Completed the baseline (no fuel load change) estimation of daily wildfire emissions to create wildfire emission inventories for the 12 cases, and merged these with anthropogenic emissions for the air quality modeling. We are continuing to work on estimating the sensitivity of wildfire emissions to fuel load changes. We are modifying the inputs to the BlueSky/CONSUME fire emissions model to capture changes in the spatial variability of the fuel loads in the Southeast by mid-century relative to the baseline spatial distribution in 2005. We are testing out these modifications to examine the sensitivity to fuel loads with a short-term study (3 months) comparing the baseline impacts on wildfire emissions to the impacts in the 2016 wildfire season in the Southeast, as we can get current data on fuel loads from the FIA database. The unusually large amounts of fuel and drought conditions during the catastrophic wildfires late in 2016 offer good data for evaluating our fuel load projection methodology. We will continue the work with modeling the future decade (2040-2050) air quality for the RCP4.5 and RCP8.5 scenarios."

Estimating the Effects of Changing Climate on Fires and Consequences for US Air Quality Using a Set of Global and Regional Climate Models (Pierce 13-1-01-4) is developing an integrated assessment of the effects of fires under different future climate scenarios on ozone, black carbon and fine particulate matter (including secondary organic aerosols) across the contiguous US. The project will attempt to quantify the effect of climate change on fire activity, vegetation and air quality over the entire US, where climate dynamics will drive fire and biogenic emissions linked directly to air quality within the same modeling framework at 50x50 km resolution. The project will quantify potential changes to fire activity and vegetation resulting from future changes in climate, develop global daily averages of area burned and fire emissions at fine scale, and assess future contributions from fires to ambient pollution levels. Preliminary results were presented at ISS2. *How future fire activity will affect mid-century air quality over the United States*, presented by Bonnie Ford and authored by Pierce and others from CSU, MIT, NCAR and the University of Sheffield, included an analysis of the changes in future wildfire activity and consequences on air quality over the United States. They focused on PM2.5 and ozone, employing the global Community Earth System Model (CESM) with new IPCC RCP projections. CESM was used with a process-based global fire parameterization to project future climate-driven and human-caused fire emissions (Li et al., 2013). Global area burned projections were similar to other published work (using SIMFIRE (Knorr et al., 2016) and SPITFIRE (Viera et al., 2016) suggesting from 30 -60% increases by 2100 in US area burned depending on the projection. Preliminary results show that after 2050, fire pollution may be the dominant source of summertime $PM_{2.5}$ in many regions across the US, and may offset benefits of reducing anthropogenic emissions. Effect of human intervention (i.e., fire ignition/suppression) on area burned suggests that demographic changes might be a key factor controlling future fire emissions.

Results show that area burned is very sensitive to population density, and future population growth may reinforce or counteract the impact of fire activity due to climate on a regional scale (e.g. tropical Africa). In future studies that project fire activity, researchers need to take into account both climate and demographic changes. Finally they analyzed changes in global area burned by landscape, peat, deforestation and agriculture fires from 1850 to 2100. Over North America, simulations showed that future changes in area burned will be more noticeable after 2080 and agricultural fires will account for about 5-10% of the total area burned across the US. Some management implications from this research include that fire pollution may be the dominant source of summertime PM2.5 over eastern US after 2050, and many states over this region may not attain the EPA NAAQ Standard of 12 ug/m^3. Eastern US is also downwind from Canada and Alaska. Increased pollution from fires over the boreal forests may impact future air quality over eastern US.

Future Fire and Smoke Impacts on Climate

JFSP funded a special project *Potential Climate Feedbacks of Changing Fire Regimes in the US: a Review* (Birdsey 16-S-1-02). This project involves reviewing relevant literature including fire emissions, national emissions inventories, climate modeling, and radiative forcing in order to assess potential feedbacks on the climate from changing fire regimes and resulting smoke. They found that both the effects of wildland fire emissions on atmospheric radiative forcing and fire-induced landscape modifications that change earth's surface influence climate. Biomass burning is considered one of the major sources of organic carbon (OC) emissions to the atmosphere. OC is likely to cause strong warming effects, not only from its black carbon component but also from other carbon aerosols whose radiative climate impacts are less well quantified in most climate models. Aerosol and related VOC emissions vary considerably across vegetation and fuel types, vegetative state, species composition and with regard to fire intensity. This makes quantification of emissions, and subsequent warming and cooling effects on climate, difficult. Poor characterization of ozone production from fire plumes largely impedes assessment of the impacts of wildfires on air quality. One example is that oxygenated volatile organic compounds (OVOCs) may account for 60-70% of VOC mass emitted from wildfire plumes, but OVOCs are not well characterized in emissions inventories. Characterization of OVOCs and their evolution in fire plumes is essential to assess the impact of fire emissions on regional and global air quality and climate. Some management implications from this study are that the biggest challenge in quantifying the impacts of wildland fire on climate is the lack of high-quality and extensive data streams for fire occurrences and emissions. Fire data on fuel characteristics, burn severity, burn area, fuel consumption and the fire weather, all at appropriate spatial scales, is especially important. Current estimates show that carbon emissions from all fires in the US are comparable to the net uptake of carbon from the atmosphere by forests in the US; meaning that US forests may not be a net carbon sink when fires are taken into account. Three key issues for future mechanistic studies of fire feedback to climate are: the composition and dynamics of fire-emitted aerosols and their functional mechanisms in radiation budget and cloud formation, clarification of the role of secondary products from fire emissions in radiative budgets and atmospheric boundary processes, and the use of a coupled modeling approach with ground and satellite derived data to investigate the mechanisms and contribution of fire-induced vegetation dynamics, land use and land cover changes to climate.

How is This Theme's Information Being Used?

- The two literature reviews completed under this theme have clarified both how to project fire air quality impacts into the future under a changing climate but also how fire emissions may impact regional climate.
- New information has been gained about methods to downscale data from GCMs to create regional fire climate projections, a critical need for future fire management planning.
- Assessments of black and brown carbon under this theme have reduced controversy over this issue for continental USA prescribed fire.
- The understanding of the significance between feedbacks between changing climate and vegetation is now more fully appreciated and is being included in attempts at improved regional climate projections.

Remaining Challenges

This remains an active area of research. The Forest Service has recently created a comprehensive climate change resource center to provide a source for developing information and datasets of future climate (http://www.fs.usda.gov/ccrc/library/climate-data). The UN's IPCC that published its last assessment report, AR5, in 2014 is already fully engaged in its next assessment report scheduled for release in 2022. The IPCC reviews the science of climate change and its effects. There are thousands of citations of research papers included in the report and hundreds of new papers are being published annually on the subject. Linked issues associated with climate change, fire and air pollution are among the current research areas receiving considerable attention by the world community of researchers so it is very likely that this area of research will continue into the future.

Among the reasons why it will be a continuing area of work is that all of the studies that have been done to date have significant limitations. There are complex interacting nonlinearities between the physical-biochemical climate systems that lead to very different results depending on which assumptions and the manner of parameterization selected for the research. Because of the non-stationary nature of both the changing climate and evolving ecosystems there can be only limited reliance on statistical approaches.

Fire and the smoke it generates occurs, by in large, at a local scale while the tools used for the analysis of climate change are global. There are large scale differences that must be bridged for these studies and significant errors are introduced as a result. More and better regional climate scenarios need to be developed.

In the modeling simulation studies conducted for this Theme (e.g. Liu, Pierce and Shankar) one of the more uncertain aspects has been the simulation of future fuels and future fire. The state of the science in vegetation system modeling, especially at the scales needed for the regional simulations presented here, is quite uncertain. The subsequent relationship between the simulated vegetation and fire fuels and fuel conditions generates even greater uncertainties. The nature of the fire itself is not only dependent on the weather and climate but also on a number of relatively unpredictable social factors. This is highlighted by Pierce in their work to date. And better regional air quality simulations with improved emissions inventories and more realistic chemical process mechanisms for both gases and aerosols will be needed.

Finally it must be recognized that these climate driven processes are stochastic in nature meaning they will always remain, to a certain degree, unpredictable so that ensembles and extreme and nonlinear events will always be present. This stochastic nature leads to the conclusion that smoke impacts from future fires in a changing climate will remain highly uncertain. JFSP supported research has served to illustrate the breadth of potential for future smoke impacts. Continued research by the climate change community will lead toward better regional climate and associated ecosystem projections. As these improvements develop JFSP may wish to consider further investment in fire and smoke consequences.

SSP CONCLUSIONS

We believe that Joint Fire Science Program SSP activity will conclude (after all funded research projects reach conclusion in about 2018) with meeting its four theme goals successfully. This is a very optimistic statement that some may disagree with, but, it would be hard for even the harshest of critics to not acknowledge that much focused science towards the theme goals was funded with significant useful results obtained. To step back and gain perspective, the SSP was only one facet of the JFSP Smoke Line of Work. The entirety of the line of work was the plan along with its processes of development, implementation, and resultant impacts.

Perhaps one salient point to make is that if the SSP was a successful addition to the JFSP it has been so due to the partnerships it engendered. Such partnerships aided JFSP to reach out more broadly and engage with new investigators, bringing new approaches and ideas into the line of work. This is especially true for the work on smoke exposure and smoke and climate change. Another example is the development of the FASMEE project for smoke model validation, which is now underway. In these examples new areas of science have been attempted with new researchers added to JFSP.

The SSP has resulted in 41 specific research projects under four theme areas, each project being a stepping stone to achieve a theme objective. In the document *A Compendium of Brief Summaries of Smoke Science Research In Support of the JFSP Smoke Science Plan*, which is a companion to this report, each project is summarized and its progress toward SSP theme's goals identified.

JFSP SMOKE LINE OF WORK BEYOND 2017

If the SSP would someday (in the next 3 years or so) be re-instituted as a guidance document of the JFSP Smoke Line of Work, we would recommend that the four themes of the first SSP be used again as organizing principles. We give three reasons for this advice:

- The "drivers" as identified in Figure 1 (page 11) have not significantly changed;
- Each of the original themes are as relevant as they ever were, and although it is certainly possible to categorize things in a different way, these capture the waterfront of smoke research in a concise and understandable manner;
- Consistency is a virtue and these Themes remain a straightforward and valid means of communicating emerging research information to the fire and air resource management communities. User communities that will need to actively participate in any future versions of any subsequent smoke science plan.

Wildland Fire Leadership Council (WFLC) Assessment of Future Smoke Research Needs

In January 2016, the Smoke Science advisers were asked to prepare information about the Plan to support an interest expressed by the Wildland Fire Leadership Council (WFLC) concerning the state of knowledge in fire, smoke and air quality regulations. The advisors assisted JFSP leadership in preparing material for WFLC consideration. This eventually resulted in a Workshop that WFLC organized and held in August 2016. Scientists and a few managers were invited to represent a cross section of Federal Agencies and States interested in this issue. JFSP leadership and the SSP advisors presented an overview of the Smoke Science Plan and its accomplishments along with a suggestion of remaining research gaps. Following the Workshop a preliminary report was issued and the SSP Advisors were asked to critically review the report and especially to identify points of intersection between WFLC recommendation and existing Smoke Science Plan activities. The advisors prepared documents for JFSP management specifically in support of all these activities:

The result of this process (as of 30 March 2017) is a draft final report of findings and recommendations to the WLFC. This draft includes the following five recommendations for Agency follow up:

1. **Relative Impacts of Prescribed versus Wildfire** – Understanding the differences in air quality impacts, social and economic effects, and impacts to ecosystem services
2. **Public Health, Behavior, and Communication**
    a. Need to determine and consider human health short/long term exposure risk
    b. Social science study of the public response to smoke warnings/interventions
3. **Smoke Management Model Improvement** – Need for model validation, prescribed *vs* wildfire modeling, improvement of 1km weather grid availability, diurnal effects
4. **Emissions Inventory and Fuels Characterization**
    a. Emissions inventory – Standardizing terms and methods for nationally inclusive, all owner, daily database of prescribed fire and wildfire activity and emissions
    b. Fuels characterization - Dynamic and standard fuel mapping, seasonal effects on consumption, fuel loading change history, standard emission factor approaches
5. **Basic Smoke Management Practices -** Regulatory need for training and tracking use.

The Smoke Science Plan has addressed the first four of these issues extensively and it is gratifying to see a broad cross section of the fire and air quality communities endorsing essentially the same priorities and subjects as the Plan has been pursuing. The fifth recommendation is less a research activity and more an operational consideration beyond the scope of the Smoke Science Plan.

SSP Advisors Final Recommendations on JFSP Smoke Science

This is perhaps the most difficult discussion to write at the conclusion of the Smoke Science Plan. In this report, we argue that much progress has been made under the SSP. We also argue that, objectively, the SSP five-year theme objectives have been or soon will be met. We also argue the SSP has generally been, and still is, in alignment with current smoke science gaps as evidenced by the recent WFLC smoke research needs assessment. If the SSP has not actually made JFSP smoke investments more effective, it has made JFSP funding more focused and thematic.

If the SSP would someday (in the next 3 years or so) be re-instituted as a guidance document of future JFSP smoke science research, we would recommend that the four themes of the first SSP be used again as organizing principles. We give three reasons for this advice:

- The SSP Theme "drivers" as identified in Figure 1 (page 11) have not significantly changed;
- Each of the original themes are as relevant as they ever were, and although it is certainly possible to categorize things in a different way, the Themes capture the waterfront of smoke research in a concise and understandable manner;
- Consistency is a virtue and these Themes remain a straightforward and valid means of communicating emerging research information to the fire and air resource management communities. User communities that will need to actively participate in any future versions of any subsequent smoke science plan.

So, what do we as the SSP Advisors recommend, at this, the completion of our journey? Three simple steps:

1. Support FASMEE and as the program develops data, and objectively evaluate if these data are meeting needs for both smoke managers and air quality managers. The key word we suggest is "objectively." This may require independent outside review and also coordination by JFSP program management with air and smoke managers. FASMEE has much potential to address many needed science gaps for smoke, but it will not fulfill every need that will be expressed to JFSP concerning smoke by groups such as NWCG Smoke Committee.
2. JFSP may still wish to conduct a second round of smoke science roundtables, perhaps in 2018 or 2019. Doing so would help the JFSP Board of Directors determine if FASMEE and other work conducted under the SSP has met or will meet user needs. If a robust set of smoke science gaps (areas where there is no existing science available) is identified, JFSP can then assess if more emphasis on the smoke science is needed. Such emphasis might result in another version of the SSP or might not.
3. The JFSP program managers should consider writing a concise document (perhaps two pages) as to what they would like to achieve under the smoke line of work in the next three years. If the program managers see fit, this could be done using the four SSP themes. This document could then be used to guide and winnow requests for development of new research as they are advocated. It will, of course, need vetting with the JFSP Board of Directors.

APPENDICES

APPENDIX A: REFERENCES

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APPENDIX B: SSP Milestone Tracker

Smoke Science Plan Milestone Tracker

Notes: Highlighted boxes under fiscal years indicate expected duration of Active SSP projects.
Italicised *legacy projects* are those funded before or outside of the SSP, but seen as contributing to attaining SSP Theme Milestones.

Theme and Objective (JFSP project # - *legacy in italics*, active in bold)	Milestone	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16	FY 17	FY 18
Theme 1: Emissions Inventory Research Objective: To develop new science and knowledge that would support and define an accurate national wildland fire emissions inventory system.									
(11-1-6-06)	Methods to correctly inventory **smoke emissions** and assess their contribution to **ground level ozone**.	Fund							
(12-1-7-01; 12-1-7-02)	Critical **assessment of** current **inventory tools** and methods to determine where strengths and weaknesses lie.		Fund						
(12-1-08-31)	Methods to correctly inventory **smoke emissions** and assess their contribution to **ground level particulates.**		Fund						
(*09-1-03-1*; **14-1-03-26; 14-1-03-44**)	Methods to inventory **smoke emissions** contributing to **secondary organic aerosols and nitrogen**.				Fund				
(11-1-5-16**; 15-1-01-1)**	Methods for **fuels mapping** and fuel **consumption estimates** to improve the accuracy of emissions inventories.					Fund			
(**16-1-08-1,** this is a regional design)	Methodology/design for a **national consensus** smoke **emissions inventory** system that could be implemented.						Fund		
Final Theme Product: A comprehensive suite of *peer-reviewed best science* based smoke inventory methods that are ready to be used in an inter-agency effort to improve the wildland fire component of state and national emissions inventories.									

Theme and Objective (JFSP project # - *legacy in italics*, active in bold)	**Milestone**	**FY 11**	**FY 12**	**FY 13**	**FY 14**	**FY 15**	**FY 16**	**FY 17**	**FY 18**
Theme 2: Fire and Smoke Model Validation Objective: To develop the scientific scope, techniques and partnerships needed to validate smoke and fire models objectively using field data.									
(*08-1-6-01; 08-1-6-04*; *08-1-6-06; 08-1-6-09; 08-1-6-10; 9-1-04-1;* *9-1-04-5*; 12-3-1-06)	Methods to **archive**, make available, and utilize existing **field data** to test smoke models (including SEMIP).	Fund							
(*09-1-04-02*; 11-2-1-11)	**Field experiments** that provide complete data sets needed to **evaluate model** performance (fire behavior and smoke production and dispersion; Rx Cadre).	Fund							
(13-S-01-01; **15-S-01-01**)	**Interagency research plan** to conduct the field experiments needed to gather the data sets needed to **test existing smoke models** (incorporates interagency workshop on coordination - Tim Brown,, and FASMEE Phase I – Roger Ottmar).			Fund					
Anticipated future interagency field experiments	**Field experiment**(s) conducted that provide the complete data sets needed to evaluate model performance (**smoke focus** experiment rather than fire behavior focus, **proof of concept**). This is FASMEE.								
Final Theme Product: A *best-science methodology* that provides a consistent framework for evaluating smoke model performance; science agency partnerships developed that will foster additional data collection efforts to support a broader array of test cases for model validation.									

Theme and Objective (JFSP project # - *legacy in italics*, **active in bold**)	Milestone	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16	FY 17	FY 18
Theme 3: Smoke and Populations Objective: To develop the science to objectively quantify the impact of wildland fire smoke on populations and fire fighters, elucidate the mechanisms of public smoke acceptance and increase understanding of the balance between ecosystem health and acceptable smoke exposure risks.									
(**13-1-02-14; 14-1-04-09; 14-1-04-16**)	Methods to assess what ambient **smoke concentrations** endanger **public health** and whether such levels are more closely related to workplace exposure standards or ambient air quality standards.			Fund					
(**14-1-04-05**)	Methods to assess the potential for wildland fires to impact **large population centers** and the **potential severity** of such impacts.				Fund				
(*10-1-03-2; 10-1-03-7*; 12-3-01-21)	Methods by which **public awareness** can be raised about smoke as a consequence of resources management and the definition of what **factors influence smoke acceptance**.		Fund						
(13-C-01-0*1;* **15-1-02-2; 15-1-02-4**)	Methods developed so **public** can be most effectively **warned** about **smoke** hazards/**risks**.					Fund			
Final Theme Product: A *best science research warning system* for public smoke risk that can be tested for eventual adoption into air quality/pollution episode forecasts by EPA/ NOAA.									

Theme and Objective (JFSP project # - *legacy in italics*, active in bold)	**Milestone**	**FY 11**	**FY 12**	**FY 13**	**FY 14**	**FY 15**	**FY 16**	**FY 17**	**FY 18**
Theme 4: Climate Change and Smoke Objective: To gain understanding of the implications of wildland fire smoke to and from climate change using the IPCC scenarios as guidelines.									
(10-S-02-1**;** 11-1-5-12; 11-1-5-13**)**	Assessment of the potential for **long-range transport** of smoke and **black carbon** to the **arctic** and what smoke induced changes in atmospheric optical properties might affect climate.	Fund							
(11-1-7-02; 11-1-7-04)	Methods to assess the potential for large fires/**Megafires** to transport **smoke** over long distances to **large population centers**.	Fund							
(12-S-01-2)	**Methodology** to assess the future climate and **fire regimes** change, and using the IPCC scenarios, so that such changes can be **down-scaled** to a regional level and used to project **regional smoke consequences**.		Fund						
(**13-1-01-04; 13-1-01-16**)	Assessment of the **regional smoke consequences** of projected **climate change** under the IPCC scenarios.			Fund					
(16-S-01-2)	Assessment of climate driven changes in **fire regimes** and how **greenhouse gas emissions** from US wildland fire may influence future change climate.						Fund		
Final Theme Product: *Best science synthesis document(s)* that outlines air quality changes precipitated by fire regimes resulting from climate change and an assessment of how emissions from changing fire regimes will in turn influence climate change. In addition, all of the *modeling input and output files* used in analyses will be available for additional research (for example: evaluating the air quality impacts of various prescribed fire management policies under changing climate).									