State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues

Special Session Summary Report

Smoke Symposium, International Association of Wildland Fire, College Park, Maryland. October 24, 2013

Photo Credit: Craig Clements

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Introduction and Background

This special session was organized by the Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) in conjunction with the Joint Fire Science Program (JFSP) and Core Fire Science Caucus. With over 30 million acres of land throughout the United States, the DoD manages a wide diversity of ecosystems and important habitat for many threatened and endangered species. Of the 5 million acres of DoD forestland, over half are southern pine forests that are generally maintained by frequent prescribed burns. In fire-adapted ecosystems such as southern pine and western pine forests, the DoD uses fire as an important ecological restoration and forest management tool and conducts prescribed burns on an average of 400,000 acres annually. To support DoD's continued use of fire in ecosystem-based management, SERDP and its sister demonstration program ESTCP have funded efforts to characterize wildland fire emissions to meet air quality requirements, understand how fire interacts with invasive non-native species such as cheatgrass (*Bromus techtorum*) in the western United States, and demonstrate and validate fire behavior models.

To provide direction to its future research and demonstration efforts, SERDP/ESTCP is developing a fire science plan. The fire science plan has five focus areas that support DoD needs and offer areas of potential collaboration with other agencies to advance fire science: (1) fire behavior, (2) ecological effects of fire, (3) carbon accounting, (4) emissions characterization, and (5) fire plume dispersion.

Smoke emissions from wildland fires are highly dependent on accurate estimates of area burned, pre-burn fuel loading, and fuel consumption. For this reason, better understanding of wildland fire behavior is fundamental to improving estimates of fuel consumption and pollutant emissions. To assess the status of fire behavior modeling and priorities for model development as it pertains to smoke and ecosystem-based forest management, SERDP and its partners organized a special session entitled “State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues” as part of the International Smoke Symposium on October 24, 2013 in College Park, Maryland (http://www.iawfonline.org/2013SmokeSymposium).

Presenters were invited to provide a status update and summary of research needs in the following areas: fuel characterization, smoke dispersion modeling, smoke validation, next-generation fire behavior modeling, fire-atmosphere interactions, ecosystem management, and fire effects. Research and funding directions for the SERDP/ESTCP and JFSP were also presented. This report summarizes each presentation and synthesizes information into a status of fire behavior modeling, research applications, and recommendation for future research directions.

List of presentations

1) John A. Hall and Allen R. Riebau – Overview of funding sources SERDP/ESTCP and JFSP and their research/demonstration priorities
2) Roger D. Ottmar*, Carl Seielstad, Clinton Wright, Susan Prichard - State of fuel characterization and consumption for wildland fire planning
3) Narasimham (Sim) K. Larkin – State of smoke dispersion modeling for wildland fire planning
4) Timothy J. Brown*, Craig B. Clements, Sim Larkin – Results from the JFSP smoke model validation workshop
5) Mark A. Finney* and Jack Cohen – Operation fire modeling and critical research questions
6) William R. Mell* and Rod Linn – Future of coupled fire-atmospheric modeling
7) Craig B. Clements – State of fire-atmosphere interactions research for smoke and fire behavior modeling
8) J. Kevin Hiers – Fire and smoke modeling to meet ecosystem management objectives
9) Matthew J. Dickenson – Trends and major gaps in fire effects research and development

* Presenter

1a. John Hall, Overview of funding sources SERDP/ESTCP and JFSP and their research/demonstration priorities

Author Bio: Dr. John Hall manages the Resource Conservation and Climate Change program area for the Department of Defense's (DoD) Strategic Environmental and Research Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP). Both programs address fire-related research and demonstration issues of concern to DoD resource managers. As an organizer for this special session, he provided an overview of fire science directions, emerging challenges, and research needs for SERDP/ESTCP.

Although the Department of Defense (DoD) is not generally viewed as a traditional land management agency, it is responsible for 30 million acres, 5 million of which are forestland. A large fraction of managed forestland is in southeastern pine, which requires frequent understory burning to maintain low surface fire hazard and open understories. The DoD underburns 400,000 acres of southern pine with prescribed fire on an annual basis and manages over 20% of existing, manageable longleaf pine ecosystems. Some of the management challenges the DoD faces regarding wildland fire include:

1) Management of fire-prone ecosystems. These include fire-adapted communities such as ponderosa pine (*Pinus ponderosa*) in the western United States and long-needled pine forests (e.g., longleaf pine, *P. palustris,* and loblolly pine, *P. taeda*) in the southeastern United States. Frequent prescribed burning of forest understories is applied to reduce fuels and potential fire hazard but is also essential for mission support, which requires open-canopied forests and open forest understories, and ecosystem-based management purposes using the principles of ecological forestry. Vegetation management decisions are driven by mission support and stewardship and are not revenue driven.

   Non-native invasive grasses and forbs have created new fire-prone assemblages in the desert Southwest, Great Basin, and Hawaii. Recent projects have been funded to better understand invasive species management, altered fire regimes, and restoration options in these altered ecosystems.

2) Prescribed fire is an integral component of silviculture and ecological forestry in fire-adapted ecosystems, but like other agencies, the DoD is challenged to maintain the use of prescribed burning programs under increasingly restrict smoke management and air quality requirements. Because smoke emissions are highly correlated with area burned and fire severity, a key research and development priority is to better understand how fire behavior relates to smoke management.

3) Carbon accounting in forest management and prescribed fire programs (including tradeoffs such as prescribed burning versus wildfire scenarios) is an emerging concern and will likely be a management priority in the near future.

4) Model validation. Given that understanding and predicting potential fire behavior is critical to predicting wildfire emissions, validation of existing fire behavior models is a big priority.

Projects that have been recently funded by SERDP/ESTCP are organized under four main project areas:

1) Air quality and prescribed burning. Four projects (FY08-FY13) focused on:
   - Emissions factor database compiled from existing studies and the SERDP-funded studies,
   - Evaluation of laboratory vs measured data/ground-based and airborne studies,
   - Stand-based emissions comparisons of fire-maintained vs fire-suppressed forests,
   - Fuel loading and consumption studies,
   - Validation of Daysmoke (Achtemeier et al. 2011) and coupling to regional air quality model, and
   - Effects of management treatments on emissions.

2) Non-native invasive species and fire-prone ecosystems in the southwestern US; three projects (FY10-FY14) focused on:
   - Science and tools to support management and restoration of southwestern US ecosystems impacted by non-native, invasive grass and forb species, and
   - Restoration of ecosystems with altered fire regimes as a result of invasive species.

3) Ecological forestry and carbon management – four projects (FY11-FY15) focused on
   - Ecologically-based forestry prescriptions and carbon management, and
   - Interactions between other desired ecosystem services (mission support, biodiversity) and carbon sequestration

4) Fire behavior model validation – 1 project (FY13-16) focused on:
   - Validating the physics-based FIRETEC model (Linn et al. 2002) using modeled simulations to measured values (fire-induced wind velocities, heat release), and
   - Demonstrating applicability of FIRETEC to prescribed burn simulations in longleaf pine fuels.

The five Core Fire Science Research Areas for the SERDP/ESTCP include 1) fire behavior, 2) ecological effects of fire, 3) carbon accounting, 4) emissions characterization and 5) fire plume dispersion.

1) **Fire behavior**. Better characterization of wildland fire behavior is critical to understanding fire effects, wildland fire emissions and tradeoffs in carbon management. Research priorities include modeling fire spread, understanding interactions between fine-scale meteorology, topography, and plume dynamics.

2) **Ecological effects of fire.** Important topics include restoring and maintaining ecosystems with prescribed fire and characterizing fire regimes, including those altered by non-native, invasive species (e.g. cheatgrass). Single-species management such as the restoration of

red-cockaded woodpeckers (*Picoides borealis*) has played an important role in the past, but the long-term goal will be for forest health and ecosystem-based management.

3) **Carbon accounting.** Life-cycle carbon accounting is seen as an emerging topic and likely a future priority for DoD land management. Research priorities include carbon accounting in forest management and under prescribed and wildland fire scenarios. Tradeoffs with other ecosystem services (e.g., mission support, supporting biodiversity) also need to be examined.

4) **Emissions characterization.** Because fire is an important land management tool, particularly in southern pine forests, emissions characterization will continue to be a research priority. Research priorities include fuel characterization and consumption studies, quantifying emissions under different fuel types, fuel loads, and distinguishing emissions from flaming vs. smoldering combustion phases of fire.

5) **Fire plume dispersion.** Research to better understand the local and regional effects of plume dispersion from prescribed and unplanned wildland fires.

Following this special session, presentations will be summarized and used to help identify research gaps and model validation needs. The SERDP/ESTCP fire science strategy will be finalized and used to coordinate with other agencies to avoid duplication of efforts as well as leverage resources for funding initiatives. The fire science strategy will be shared with JFSP to coordinate investment and implementation strategies and then implemented through SERDP Statements of Need and ESTCP topics. An important final step is to effectively communicate findings to end users, which include both DoD resource managers and air quality personnel.

In conclusion, main research areas of interest to DoD include: 1) emissions characterization that quantify the effects of prescribed burning on air quality and help maintain the use of fire as a management tool, 2) quantify and manage carbon in open-canopy forests that also maintain other ecosystem services on DoD lands, 3) advance ecological forestry as a standard practice for DoD, and 4) achieve appropriate standardization and validation of tools and models that facilitate consistent application and technology transfer to end users.

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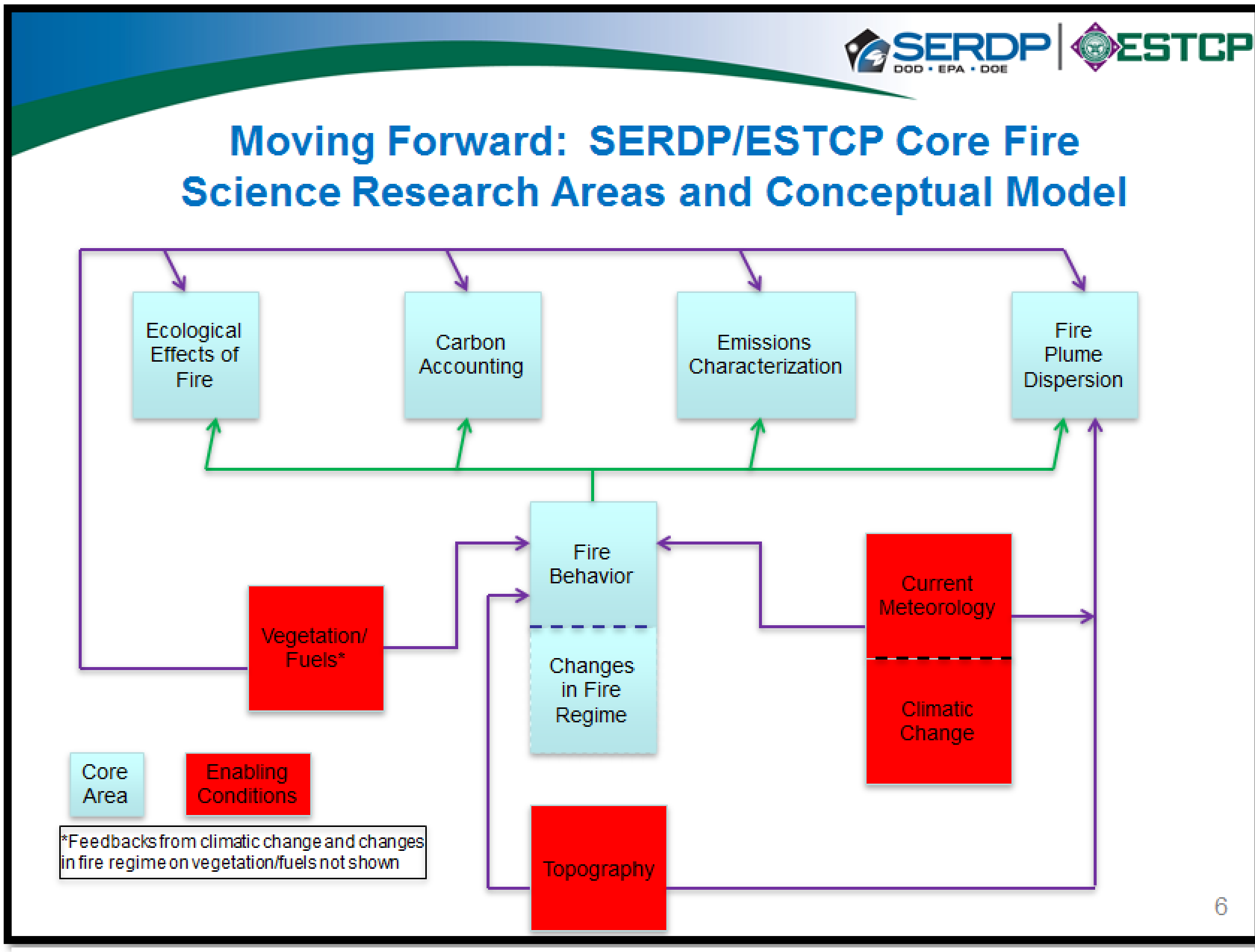

Figure 1: Conceptual diagram of SERDP/ESTCP Core Fire Science Research Areas.

1b: Al Riebau, JFSP alignment with SERDP/ESTCP

Author Bio: Allen Riebau worked in public service for United States in the Departments of Defense, Interior, and Agriculture for over 32 years. At the present time he is the Principal Scientist for Nine Points South Technical, an air quality and natural resources management consulting firm in Western Australia. His last United States federal career position was as Chief Atmospheric Scientist of the USDA Forest Service Research and Development.

Al Riebau provided a brief review on JFSP's process for identifying key research questions and directions, including potential areas of collaboration with SERDP and ESTCP. JFSP has a deep alignment and natural partnership with SERDP and ESTCP programmatic goals. Through round tables, science plans and exchange networks, JFSP is continually identifying and prioritizing key research questions in order to fund critical aspects of fire science research. Research funding is awarded through a competitive process, and findings are disseminated through regional consortia (http://www.firescience.gov/JFSP_consortia.cfm), publications and social media.

Currently, the main JFSP lines of work include fuels treatment, smoke management and model integration (IFT-DSS). Some of the critical management needs identified for JFSP funding priorities include spot-weather forecasts, threatened and endangered species, fire effects on water and cultural resources. New science initiatives include fire social sciences, fire ecology and remeasurement opportunities.

Specific to smoke, researchers didn't have the technological advances for field measurement, data assimilation and analyses that we now have to address questions regarding smoke management and wildland fire emissions. With the advent of social media and increased use of webinars, options for communicating results have also expanded.

The JFSP Smoke Science Plan (2010) identified four research themes including 1) smoke emissions inventory research, 2) fire and smoke model validation, 3) smoke and populations, and 4) climate change and smoke. Each research theme outlines yearly priorities over a five-year plan to achieve thematic objectives.

Next steps for JSFP's smoke management research directions include:

1) Fuel consumption projects. These should align well with partnerships with SERDP/ESTCP to leverage funding and expand the scope of JFSP-funded projects, and
2) Large, integrated science assessments including climate change, regional assessments, and model validation. JFSP is interested in bigger science areas than what has been addressed before and opportunities to leverage funding to support them through shared funding directions with SERDP/ESTCP and other funding and research partners.

2. Roger Ottmar*, Carl Seielstad, Clint Wright, and Susan Prichard. State of fuel characterization and consumption for wildland fire planning

Author Bio: Roger Ottmar is a Research Forester, with the Fire and Environmental Research Applications Team, Pacific Wildland Fire Sciences Laboratory, Seattle, Washington. Roger leads efforts to develop: 1) a natural fuels photo series; 2) Consume, a model to predict fuel consumption and emission; and 3) the Fuel Characteristic Classification System to build and characterize fuelbeds for the United States and the world. He consults on the assessment of wildland firefighter exposure to smoke and leads the RxCADRE project, individual researchers and research teams from across the United States that collaboratively collect data to evaluate fire models. Carl Seielstad is an associate research professor at the National Center for Landscape Fire Analysis at the University of Montana, Missoula, MT. Clint Wright is a research forester with USFS Pacific Northwest Research Station Pacific Wildland Fire Sciences Laboratory, Seattle, WA. Susan Prichard is a research scientist with the University of Washington's School of Environmental and Forest Sciences.

The objective of this presentation was to identify strategic areas in fuel and fuel consumption research required for future investment in fire science modeling. The presentation covered: 1) a review of why fuel characterization and consumption measures are important, what the current state of the science is, and what needed investments are required as we move forward. 2) how new tools such as terrestrial and remotely sensed LiDAR and SAR will provide the fuel and fuel consumption characterization for future fire modeling, and 3) a description of the recent RxCADRE project, an integrated research effort that uses a stepwise, hierarchical data collection process to efficiently acquire research knowledge across several disciplines.

Wildland fuels are extremely variable across ecosystems and are a critical component of fire behavior and effects modeling. They are both spatially and temporally variable, and adequate characterization often requires multiple sets of measurements to account for seasonal changes in the fuelbed, (e.g., leaf on and leaf off conditions in eastern hardwood forests), vegetation and fuel succession, and human and natural disturbance events such as insects, disease, wind throw, mechanical fuel treatments, prescribed burns and unplanned wildland fires.

Fuel characterization is a key component of all fire models that support decision support systems across many disciplines including smoke management, fire and fuels management, carbon accounting, wildlife habitat management, and climate change assessments. The appropriate characterization of the fuelbed is especially important for modeling of smoke from wildland fire and predicting air quality impacts. In particular, fuel loading and consumption represent the two largest errors in emission characterization and production estimates.

Wildland fuels can be characterized by traditional measurement methods such as line intercept (Brown 1974) and clip plots. There are also biometric equations, photo series, pile loading, photo load (Sikkink et al. 2009) and now ground- and aerial-based LiDAR (Seielstad et al. 2011) techniques that can be used to characterize fuels that can reduce workloads but often at the expense of accuracy. As fire models become more sophisticated (e.g., physics-based models such as WFDS and FIRETEC), they will require improved characterization of the physical properties and spatial distribution of the fuels. There will be an increasing need for three-dimensional, high-resolution fuels and reliance on terrestrial and remote sensing. These remote sensing techniques have an advantage in that data can be collected without disturbing fuels, traditionally a challenge in pre- and post-burn fuel sampling.

Broad-scale mapping of fuel loads are constrained by a data type mismatch between satellite images, which generally capture canopy characteristics (e.g., vegetation type and cover) and surface fuel loads important for fuel consumption estimates. For example, pre-fire fuel load estimates available for the 2006 Tripod Complex fires (Figure 2) demonstrates large differences in fuel estimation for a forested landscape in north-central Washington State. Options to validate and rectify fuel mapping datasets are limited.

There are several key research and development needs to better improve our ability to characterize fuels:

- Improved methods to characterize all fuelbed components (e.g., organic soils, tree cones),
- Characterization of new fuels and vegetation assemblages (e.g., masticated fuels, homes and landscapes within the wildland-urban interface, and invasive species assemblages),
- Improved high-resolution and three-dimensional fuel measurements required for next-generation fire behavior models (e.g., LiDAR, Synthetic Aperture Radar, SAR),
- Measurement of fine-scale bulk density surface area-to-volume ratios, and spatial location of fuel particles within wildland fuelbeds,
- Validation and testing of current and future measurement techniques,
- Creation of a central data repository of fuel characteristics and consumption studies to assist with validation and testing, and
- Improved methods for mapping and spatial positioning of both surface and canopy fuels.

Current fuel consumption models have had minimal validation to date and contain data gaps (e.g., Northeast hardwoods in Consume). Investments are needed to develop a consistent, robust evaluation data set to evaluate and refine consumption algorithms in Consume (Prichard et al. 2007), FOFEM (Reinhardt et al. 1997, Reinhardt 2003) and the Canadian Fire Effects Model (CanFIRE, de Groot et al 2007). Consumption models need to be developed for fuelbed types and components not addressed in current models, including masticated fuels, tree crowns and WUI homes and landscapes. Further work is also needed to estimate consumption by flaming, smoldering, and long-term (residual) smoldering combustion and to better represent the role of fuel moisture in predicting fuel consumption. Finally, fuel consumption can now be estimated by next-generation fire behavior models, and additional inputs and validation will be necessary for broader application of these models.

Recent advances in LiDAR and SAR have greatly improved fuel characterization by representing fuelbed structure at fine (i.e., submeter) resolution and across forest stands (>1000 ha) (Seielstad et al. 2011). However, more work is needed to calibrate remotely-sensed images to on-the-ground field measurements.

Future work with LiDAR- or SAR-based fuel characterization will require an integrated approach with fuel and fire behavior modelers to apply remote sensing sampling techniques to heterogeneous fuel complexes, perform sensitivity analyses, and address important scaling issues such a scaling small burn units to landscapes. The recent RxCadre experiment is an example of a successful, integrated approach between modelers and sensors and has made use of LiDAR-based fuel characterization and ground-based field sampling.

In conclusion, several major research needs for fuel and fuel consumption characterization include: 1) refine field data sampling methods including LiDAR for fire model inputs, 2) improve fuelbed maps and validation techniques, 3) collect systematic measurements of fuel consumption by fuelbed component (e.g., shrubs, herbaceous fuels, woody fuels by size class, litter and duff) and combustion phase, 4) move toward physics-based fuel consumption modeling, 5) improve fuel moisture modeling, and 6) promote integrated research approaches with direct communication with modelers.

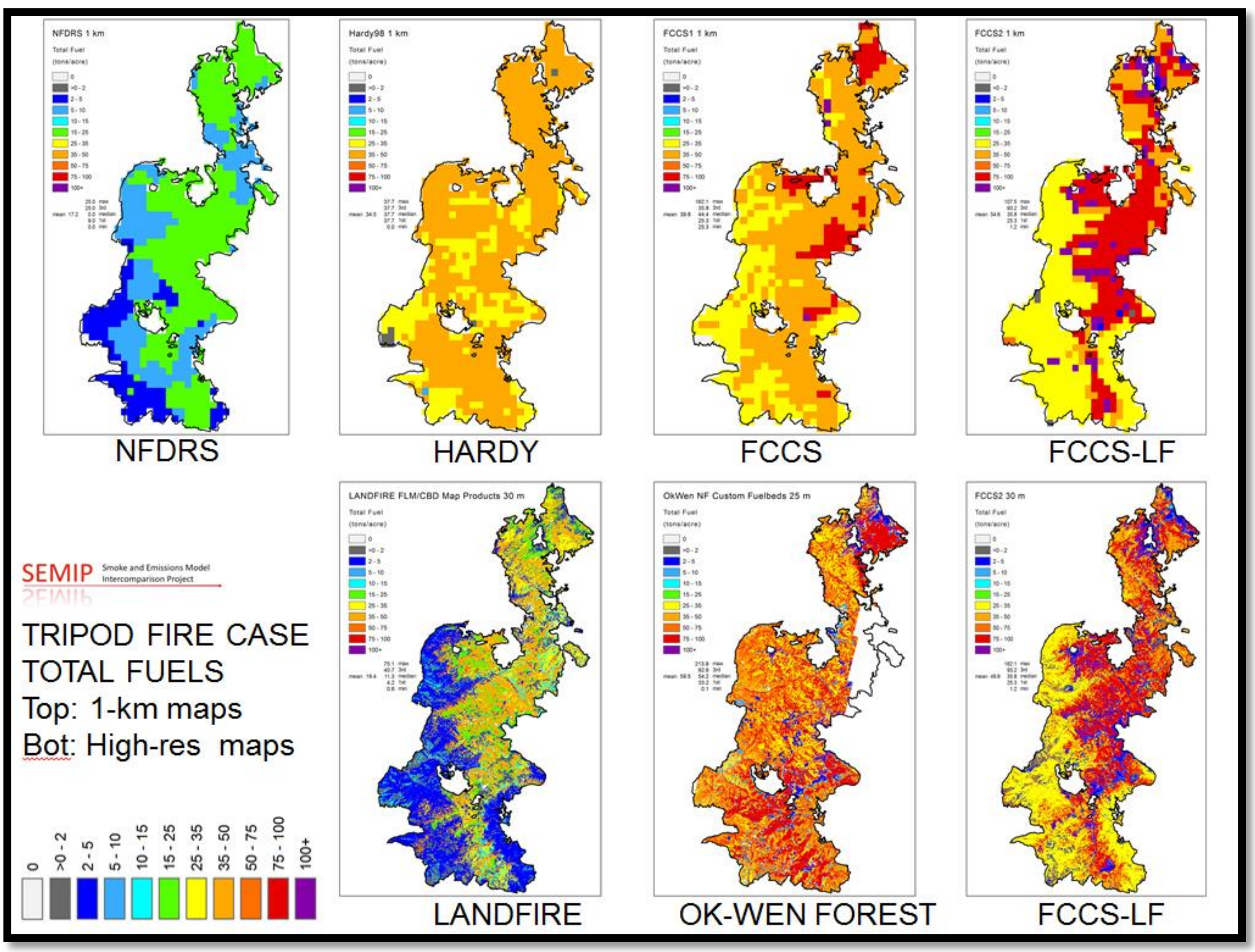

Figure 2: Demonstration of widely different estimates of pre-fire fuel loads for the 2006 Tripod Complex Fire in north-central Washington State (Drury et al. *in press*).

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3. Sim Larkin, State of smoke dispersion modeling for wildland fire planning

Author Bio: Sim Larkin is a Research Physical Climatologist and Team Leader of the U.S. Forest Service AirFire Team of the Pacific Wildland Fire Sciences Laboratory in Seattle, WA. He conducts research in applied climatology, fire emissions and air quality, with an emphasis on the application of data analysis, statistical methods and scientific visualization. His primary research topics include analysis of wildland fire-climate and fire-air quality relationships and applications product development for wildland fire management planning, decision-making and policy. Dr. Larkin is the original designer of the BlueSky Modeling Framework used around the world for real-time and retrospective smoke modeling, and the creator of the SmartFire2 system used by the U.S. EPA and other agencies for fire activity and emissions inventory development. He created and led the Smoke and Emissions Modeling Intercomparison Project for JFSP, an on-going effort to provide a mechanism for testing, comparing, and assessing developments within fuels, consumption, emissions, plume rise, and smoke modeling.

A basic definition of smoke modeling is that it uses fire information and weather predictions to estimate smoke impacts. Currently, there are wide range of smoke prediction tools and models including simple spreadsheet tools, stand-alone models or software applications, web tools, daily forecasts, custom models and coupled fire-atmospheric models. With all of the available models, a common question for smoke modelers and managers alike is, “How well do smoke models work?” The published literature on smoke model evaluation ranges from anywhere from poor to very well. It may be more useful to reframe the question into, “How well do models work for specific applications?” Predictive models are generally used on a daily or routine basis and tend to have low accuracy. In contrast, retrospective or custom models for a specific project generally offer the most accurate predictions but are not suitable for daily or routine applications.

Consideration of tradeoffs is important when evaluating smoke models. More complex modeling efforts require intensive inputs and a need for training and expertise to interpret outputs. Simpler models are generally accessible to a broader user base and require few input variables, allowing for routine use and repeatable results that are readily interpreted by users. Model assessments generally involve pairwise comparisons between predictions and measured data without consideration of model utility. For smoke modeling, an example shortcoming of this approach is that a complex smoke dispersion model may be highly accurate but results may not be in time to be useful. To increase the timeliness and accessibility of predictive models, there is generally a tradeoff between model accuracy and model utility. Ideally, we would try to apply what we do best in complex modeling to make improvements in predictive or routing modeling such as daily smoke forecasts. Improvements to routine and predictive models will require substantial advances in technology, automation, better input data, and training for informed interpretation of model results.

Typical errors in smoke modeling can include initiation error (e.g., estimated inputs), problems of interpretation, and model approximation errors. Initialization issues affect the areas in smoke modeling that we wish would affect us the least – daily or routine smoke forecasting. Compared to weather forecasters with a high resolution of weather stations throughout the country, smoke modelers have ten to one hundred times fewer monitoring stations. Unfortunately, smoke has much smaller decorrelation scales than weather variables (e.g.

temperature), so the lack of air quality monitoring stations can result in substantial initiation errors in daily smoke forecasts. Problems of interpretation in smoke forecasts can become even more acute because they are not generally interpreted by trained specialists.

The recently completed Smoke and Emissions Model Intercomparison Project (SEMIP, JFSP project 08-1-6-10; Larkin *in review*) evaluated model uncertainty across interrelated steps to smoke dispersion modeling including fire shape and area, fuel loadings, total consumption, rate of consumption, speciated emissions, vertical plume profile, and dispersion/trajectories (Figure 4). The SEMIP project found model uncertainty to be dependent on the type of smoke modeling application (Table 1). For single-event emissions, fuel loading inputs and availability of appropriate emissions factors are the major sources of error. In contrast, plume rise and timing are the most important predictors of smoke dispersion from single-events. For regional emissions inventories, fire information (e.g., fire area and location) and fuel load inputs are the most important sources of error whereas regional air quality is most dependent on fire information and predicted plume rise.

Table 2: Conclusions from the Smoke and Emissions Model Intercomparison Project. Fire information includes fire size, shape and location.

Application	**Major sources of uncertainty**
Emissions from a given fire	Fuels and emissions factors of lesser-known chemical species
Smoke from a given fire	Plume rise and fire timing
Regional emissions inventory	Fire information, fuels, and emissions factors of lesser-known chemical species
Regional air quality	Fire information and plume rise

Current models offer reasonable predictions of plume shape and overall regional impact levels of smoke pollution. Some of the issues that smoke modelers still face are to:

- Refine near-field, near-drainage predictions,
- Improve meteorology including boundary layers, grid scale and terrain effects (e.g., drainage flows), and
- Provide better initialization of model inputs including improved fuel characterization, fuel moistures, fire growth, fire growth estimation and plume rise.

Several refinements are needed for process models with known inadequacies including plume rise modeling, timing, fire growth, and plume chemistry. In particular, additional model development and testing is needed to improve current plume rise models. Most plume rise models still rely on a simple representation plume rise from smoke stacks and tend to overpredict smoke from large fires and underpredict smoke from small fires.

Another important component of improving smoke prediction is to facilitate and promote interpretation of model results. One of the key differences between smoke and weather forecasting is that weather forecasters interact more with model outputs whereas smoke forecasting is much more reliant on model outputs. Future model development should facilitate interpretation of outputs for model users.

In conclusion, recent technological advances will allow for significantly better smoke forecasting systems with improvements in fire growth modeling for area burned and diurnal timing, coupled dynamic plume rise modeling for better injection, and improved understanding of plume chemistry. We have the capability in the next few years to incorporate fire growth modeling to create the next generation of smoke models. A key challenge will be to collect validation data in order to support development of these next-generation models. Although there is clearly room for improvement, current models do benefit decision makers. At regional scales, models add confirmation and quantification of expert's judgment. At local scales (e.g., smoke management planning), less experienced users are obtaining better estimates than they could generate on their own.

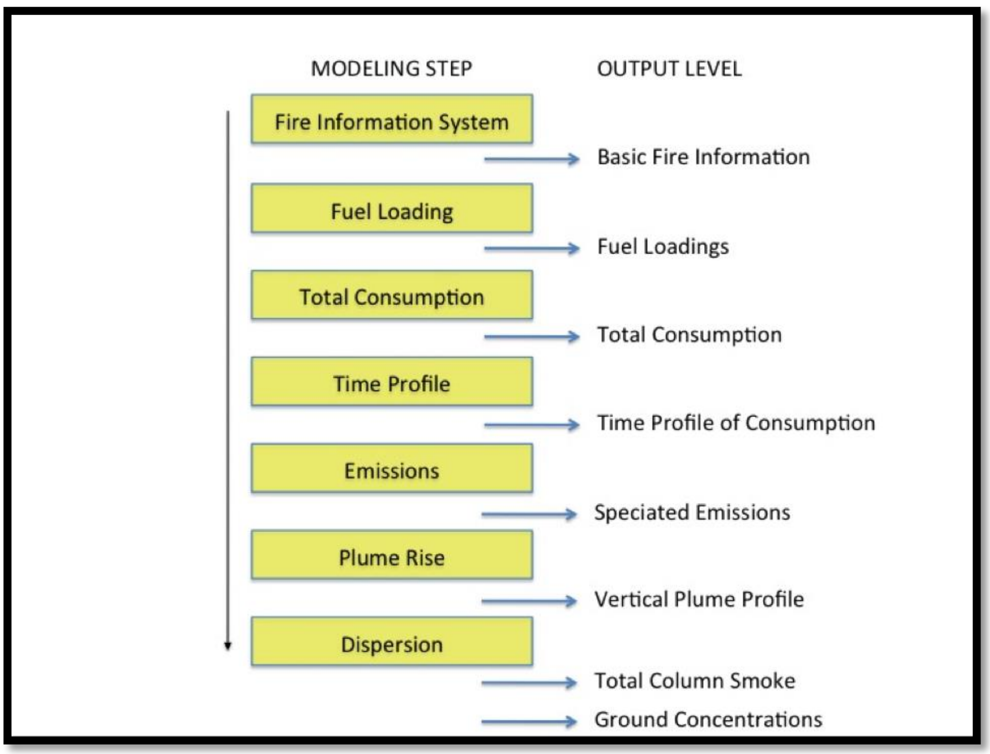

Figure 3: Modeling chain including modeling steps and output levels identified and examined by SEMIP (Larkin et al. in review).

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4. Tim Brown*, Craig Clements, and Sim Larkin. Results from the JFSP Smoke Model Validation Workshop

Author Bio: Tim Brown is the director of the Western Regional Climate Center, and the Program for Climate, Ecosystem and Fire Applications (CEFA) at the Desert Research Institute in Reno, Nevada.

A smoke validation workshop, funded by JFSP (13-S-01-01), was held in September 2013 at the Desert Research Institute (Reno, NV) to support the validation of fire behavior and emissions models. The objectives of the workshop were to 1) formalize the research elements and strategies needed to advance smoke modeling and 2) design and plan a field campaign that can significantly advance our understanding of smoke and improve current modeling systems.

Participants represented a diverse set of disciplines and organizations (Table 3) including the U.S. Forest Service, the Canadian Forest Service, NASA, EPA, JFSP, and universities. Discussion questions included:

- What are the smoke operational needs (in terms of both observations and model predictions)?
- What can realistically be expected from smoke models, including accuracy and repeatability of simulations?
- How can smoke models be adequately tested and validated in terms of these needs?
- What must be done to create the next generation smoke model(s)? We have a lot of smoke models now; the goal will not be to create a new model but to scientifically advance existing models.
- How do we ensure the next generation smoke model is grounded in observational evidence?
- What factors should be considered in designing a smoke field experiment?
- What has been learned from Rx Cadre that can be incorporated into field studies for smoke modeling?
- How can smoke model validation field studies help add knowledge to fire behavior modeling?
- How can smoke model validation field studies help validate or test air quality models such as those used in regional air quality analysis, State Implementation Plan development, and air quality forecasting?
- What is the most viable plan (e.g., research strategy/plan with potential intellectual and financial supporters) for performing a smoke field campaign that meets the above considerations in the next 2-3 years?
- To what extent should international partnerships be utilized in a field experiment?
- Which agencies would benefit from a field experiment partnership?

Focus areas were formed to organize discussions into the following topics.

1) Fire Behavior Modeling and Measurements
    - Field measurements
    - Fire-atmosphere interactions
    - Field studies

2) Multi-scale Emissions and Smoke Measurements
    - Smoke sampling / aircraft measurements
    - Satellite / remote sensing of smoke emissions
3) Air Chemistry and Smoke Modeling
    - Smoke chemistry modeling and dispersion
    - Mesoscale dispersion modeling
    - Operational smoke modeling
4) Fuels Consumption and Measurements
    - Fuels / fuel loading and sampling
    - RxCADRE lessons learned
5) Smoke Management and Agency Overviews
    - EPA wildland fire emissions products and needs
    - Canada smoke management
    - NOAA UAS program (P3 aircraft)

Phase I of the validation study will involve a preliminary model evaluation (proposed years 1-1.5) and will concentrate on how to validate next-generation, coupled fire-atmospheric fire behavior models including the Weather Research and Forecasting model (WRF-Fire; Mandel et al. 2011), ForeFire (Balbi et al. 2009, Filippi et al. 2011), FIRETEC (Linn et al. 2002), and the Wildland Urban Interface Fire Dynamics Simulator (WFDS; Mell et al. 2007). Results from the validation studies will also be available to improve operational models including FARSITE (Finney 1998), FSPro (Fire Spread Probability), Promethius (Tymstra et al. 2009) as well as models within integrated applications such as the BlueSky Modeling Framework (http://www.airfire.org/bluesky), Wildland Fire Emissions Inventory System (WFEIS; http://wfeis.mtri.org), Integrated Fuel Treatment Decision Support System (IFT-DSS; http://www.firescience.gov/JFSP_ifftdss), and Congestion Mitigation and Air Quality Improvement program (CMAQ ; http://www.fhwa.dot.gov/environment/air_quality/cmaq). Primary topics for model evaluation will include fire growth, fuel consumption and plume structure prediction.

Phase 2 will create a study design and execute a field sampling campaign (proposed years 2-5). Interagency and international partners (e.g. Canada, Australia, and Europe) will be contacted and encouraged to participate. Workshop participants recommended a case study approach in one to two locations involving three to four large burns. Preference will be made to multi-day, very large events with heavy pre-burn fuel loads and high-severity fire. Rapid response to a wildfire event would be ideal but difficult to coordinate. One to two high-severity prescribed fires are more realistic. Other possibilities might be to burn a residual patch within a recent large wildfire or effectively create an island of fuels bordered by defensible fuel breaks. A key challenge will be to logistically coordinate instrumentation with the timing of the fire event.

Phase 3 will involve model evaluation, including a synthesis of validation results, presentation of findings and implementation for operations (proposed years 3-6). Model performance, including computational time and requirements and sensitivity to input errors, will be evaluated. Iterative testing will be employed to allow modification of inputs and refinement of outputs based on validation datasets. Validation metrics will include fire growth, fire behavior, fuel consumption, pollutant emissions, plume structure, downwind plume location, plume chemistry, and ground smoke impacts.

Project deliverables will include validation datasets (i.e. collected observations, along with metadata and sampling descriptions available for download), documents (i.e., final report, published papers on validation dataset and a wide range of model evaluations, and a report providing guidance on future model refinements) and a code repository to disseminate improved code for the various models.

Table 3: Workshop participants and affiliations

Participant	**Organization**	**Position, workshop role**
Bret Butler	USFS Missoula Fire Lab	Research mechanical engineer (fire behavior)
Scott Goodrick	USFS Southern Research Station	Research meteorologist
Narasimhan (Sim) Larkin	USFS Pacific Wildland Fire Sciences Lab	Research physical climatologist (BlueSky)
Ruddy Mell	USFS Pacific Wildland Fire Sciences Lab	Research combustion engineer (WFDS)
Roger Ottmar	USFS Pacific Wildland Fire Sciences Lab	Research forester (fuel characterization, consumption)
Shawn Urbanski	USFS Missoula Fire Lab	Research physical scientist (meteorology, emissions)
Charles Ichoku	NASA	Research physical scientist (meteorology, emissions)
Kerry Anderson	Northern Forestry Centre, Canadian Forest Service	Fire research officer (fire growth modeling)
Craig Clements	San Jose State University	Assistant Professor, (micrometeorology and behavior of wildland fires)
Gail Tonneson	University of California, Riverside (EPA)	Research scientist (atmospheric research, pollutant emissions)
Brian Lamb	Washington State University	Professor (air quality, atmospheric modeling)
Al Riebau	JFSP	Consultant (JFSP smoke science plan)
Doug Fox	CIRA, Colorado State University (emeritus)	Senior Research Scientist, Emeritus (Project oversight)
Adam Watts	Desert Research Institute	Assistant professor (Fire ecologist)
Tim Brown	Desert Research Institute	Professor (Climatology, project organizer, facilitator)

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5. Mark A. Finney and Jack D. Cohen. Operation fire modeling and research directions

Author Bio: Mark Finney is a research forester with the Missoula Fire Sciences Laboratory. His research focuses on fire behavior fundamentals and operational fire modeling. Jack Cohen is a Research Physical Scientist for the Missoula Fire Sciences Laboratory.

This presentation reviewed operational fire modeling and what the limitations within current models portend for fire research. With the large number of predictive models available, modeling isn't a limiting factor in advancing models but rather understanding the underlying phenomena.

On average, over 80,000 wildland fire incidents occur in the United States per year and burn 4-10 million acres of land. Approximately 3% of all fires are responsible for 95% of the annual area burned by US wildfires. Wildland firefighting operations are provided by federal, state, county and city firefighters.

Federal land management agencies are required to report wildland fire incidents and response strategies using the Wildland Fire Decision Support System (WFDSS; Tabor et al. 2013). The WFDSS contains geospatial vegetation and fuels data (LANDFIRE and regional), fire locations and history from MODIS data (http://modis.gsfc.nasa.gov/), National Weather Service data, point and zone fire weather forecasts, geospatial values data including housing and infrastructure, WindNinja (http://www.firelab.org/research-projects/physical-fire/145-windninja) to compute wild fields for fire behavior modeling, and operational fire behavior models.

There are four main operational fire modeling methods in WFDSS including:

1) Short- and near-term fire spread modeling for one fire using a single, static weather scenario using FARSITE (Finney 1998) and Minimum Travel Time methods (Finney 2002),
2) FlamMap (Finney 2006) to evaluate many fires across landscapes using a single, static weather scenario,
3) FS Pro (Finney et al. 2011) to evaluate multiple weather scenarios for a single fire, and
4) FSim/general risk burn probability modeling (Finney et al. 2011) to evaluate many weather scenarios over multiple fires.

The authors analyzed recent WFDSS usage and found that only 3.4 % of all fires on federal land had any analysis conducted with operational fire behavior models. One of the likely reasons for the low percentage of modeled runs is that most fires are immediately suppressed. Of the modeled federal fires, basic runs using FlamMap or Behave (Andrews 1986, Andrews and Chase 1989) were conducted on 4% of fires, short-term (1-3 day) models using Minimum Travel Time accounted for 24% of fires, near-term (1-7 day) FARSITE runs accounted for 37% of fires, and 7-30 day ensemble predictions using FSPro accounted for 35% of fires.

One of the most important benefits to fire operations is that they facilitate wildland fire training and understanding of the basic principles of fire behavior. For example, Rothermel's (1972) surface fire spread model is still in use within operational fire models because it provides reasonable results, is generalizable and flexible for wildland fire planning and operations, useful in training on basic fire behavior, and practical in that it uses meaningful fuels and weather inputs.

An important characteristic of all operational fire modeling is that uncertainty dominates all inputs and observations. Therefore, efforts to validate and improve upon inputs have questionable value. Agreement between observations and model results can arise for non-unique combinations of inputs just by luck. A summary of how wind speed and fuel moisture affect measured rate of spread (Sullivan 2013) provides an illustration of the broad range of relationships found from past empirical studies or assumed functions. This illustrates how poorly the processes of fire spread are understood. Uncertainties in fire behavior modeling underscore the need for fundamental research to understand how fires spread and constraints to fire spread (e.g. fuels, wind, moisture, live and dead biomass).

The Missoula Fire Laboratory is doing basic fire research to instruct next-generation fire modeling. Some of their recent work has been on radiative heating and convective cooling of fine fuel particles and studies of boundary layer and buoyancy dynamics. For example, convection is required for ignition, but given their heat and buoyancy, how can flames maintain contact with fuel? Recent experiments have demonstrated how buoyancy dynamics involve intermittent pushes of the flame into the fuelbed, which facilitates flame contact. In another set of experiments, they have observed flame towers at fine spatial scales in the laboratory and across landscape burns. These are likely caused by Görtler Vortices (Jeschke and Beer 2001) where buoyancy dynamics result in upward and downward convergence zones and create flame towers and troughs. This phenomenon has also been observed across large landscapes, including Australian bush fires and Alaska boreal crown fires (Swearingen and Blackwelder 1987, Coen et al. 2004). Buoyancy dynamics are extremely periodic and can be represented by calculated frequencies and scaling constants (e.g., the Strouhal-Froude scaling number). Most models assume a constant rate of heat transfer to fuels, but these observations suggest that heat transfer is anything but constant.

In conclusion, basic research on fire behavior in the laboratory with field validation is essential to improve fire behavior modeling. Operational and, in fact, all fire spread models are limited by our current understanding of fire spread and depend mostly on assumptions of how fire spread occurs. Research on fire spread in the laboratory with field confirmation is essential for advancing both modeling and understanding of how fires spread.

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Morning Session Q&A

Q1: How can smoke modeling be used to understand underlying processes?
Sim Larkin: Once smoke is in the atmosphere, dispersion of particulates is well understood. Plume chemistry and emissions factors for certain pollutant species are not well known. In particular, plume rise is not well described and relies on both forecast and process.

Q2: Colin Hardy asked about research/efforts to understand underlying heat flux and energy release to plume rise.
Sim Larkin: The relationship of heat flux distributed over landscapes is a critical to estimate plume rise. Any omission in my presentation was not intended to suggest that it wasn't important or overlooked in priorities.

Q: Does fuel homogeneity in the Rothermel (1972) spread model and lack of ability of Rothermel fuel models to capture inherent heterogeneity influence general overestimation of fire spread?
Mark Finney: Rothermel has coarse-grained input which may contribute to overestimation of spread in Behave and FARSITE.

Roundtable discussion:
Kevin Hiers: the 3% wildfires (i.e., large wildfires accounting for the vast majority of area burned) and prescribed fires are really the target of the next-generation models and validation of these physics-based models

Mark Finney: We need to have specific questions for prescribed fire observations.

Tim Brown & Sim Larkin: Smoke validation study participants opted to focus on a few heavily instrumented wildland fires (Rx or rapid response WFs). A six year timeline was suggested to adjust study design and models.

David Weiss: The US has funded large-scale plume/behavior experiments since the 1970's. In total, the huge field campaigns and investments probably only had incremental benefits. Dave strongly recommended that the next validation studies do a retrospective to evaluate available data and lessons learned from past case studies.

Roger Ottmar: The Rx Cadre experience of multidisciplinary study was that groups had different needs for type of fire. Fire effects and air quality researchers required larger, operational fires in complex fuels. Fire behavior modelers wanted simpler (i.e., grassland) fires to capture the basic fire behavior concepts.

Sim Larkin: Is there a need to develop baseline test cases for which to evaluate models? This could be a synthetic dataset intended to allow cross-model comparisons at different scales. Sim thought that with the intensive data needs of next-generation models that it was unlikely past experiments would be able to fully parameterize current models.

David Weiss and Craig Clements: The Flambo study did not have a good data management plan and lost some critical people soon after the study was completed. The data loss with subsequent layoffs was a good lesson learned.

Craig Clements: with the technology such as LiDAR getting increasingly sophisticated, we now have the tools to characterize plume development. With every experiment, we are getting better and better data.

Roger Ottmar: JFSP now requires extensive data management plans and data archives with useful metadata.

John Hall: Did the smoke validation workshop identify validation criteria?
Tim Brown: validation criteria will include:

- Evaluation of which parameterization approaches work better (inputs).
- Run test cases – select which parameters to measure and help with validation.
- Compare observations with model outputs to determine how well they compare.

Unknown participant – couldn't fire behavior analysts (FBANs) contribute to validation datasets based on observations and WFDSS predictions?

Sim Larkin: Responded to Mark Finney's comment that most fires have no fire associated fire modeling. The BlueSky framework has daily smoke models runs on 70,000+ fires per year and Clients depend on these runs; many people need fire spread information for emissions estimation.

Mark Finney: responded that validation is impossible. We can never know enough about a real fire to rule out inadequate inputs (e.g., fuels, moisture, wind).

Kevin Hiers: wondered if phenomenological validation (e.g., what Ruddy Mell has done with WFDS) is the next approach. Can you capture certain elements of plume rise or Görter Vortices, etc.?

Charles Ishoku (NASA): highlighted the relevance of satellite imagery to validation – especially through retrospective modeling. Larger fires are the ones FBANs model and the ones captured by satellite imagery.

Bill – NASA field campaigns offer important datasets. What about NEON?

Doug Fox: Speaking of the JFSP smoke plan, one concern is if users are getting the information that they need and will be useful to them. Doug recognizes that validation will have different objectives and potential applications (e.g., PM_{25}, radiative char of smoke, plume chemistry). Could we attract other interested parties to leverage funding for validation studies?

Jim Roberts: NEON (NASA Educators Online Network; http://www.nasa.gov/offices/education/programs/national/nes2/home/NEON) may be willing collaborator and has an emissions map of the United States. Dave Schimel is interested in working with rapid response teams.

Kevin Hiers: Worked with NEON at Jones Center (Ichauway). They discussed studying the same fire, but because of the limitations of the eddy flux infrastructure, they didn't have the capacity to burn underneath the towers. Future collaborations with NEON should be promising, particularly in studying carbon and ecosystem dynamics.

John Hall: could we collect other data for validation that would cross disciplines (e.g., ecological effects)? For example, what are ecological effects of fire behavior and are there opportunities for synergistic approaches (wildlife, smoke, carbon accounting). John commented that we can't stovepipe each tradeoff to management; all factors have to be considered in prescribed burn plans. We have to account for smoke, carbon accounting, ecosystem impacts and benefits – it's all of these questions that we will need to answer when we prescribed burn.

Colin Hardy: Penny Morgan has a lessons-learned paper on integrated research (Lentile et al. 2007). One of the potential pitfalls is measurement without asking key questions to guide the sampling effort. Any subsequent effort needs to address lessons learned. Colin also mentioned a FEM series of papers coming out on wildfire carbon emissions (Sommers et al. in press).

Kevin Hiers: had a question on laboratory-to-field scaling for Mark Finney. Do we have the opportunity to draw inferences of larger scale phenomena (e.g., heat transfer, scaled physics, and atmospheric coupling)?

Mark Finney: Convection/buoyancy dynamics should scale up (from laboratory to field observations). Major scaling factors, once determined, should inform field experiments.

David Weiss: The whole issue of scaling a fire is the complexity of inputs and dynamics. At least 27 groups of variables contribute to plume rise and dispersion. David cautioned that not everything scales up from the laboratory to field.

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6. Ruddy Mell* and Rod Linn – Future of coupled fire-atmospheric modeling

Bio: Ruddy Mell is a combustion engineer with the U.S. Forest Service who has been involved with computer modeling of wildland fires and wildland-urban interface (WUI) fires for the past 10 years. Prior to entering the field of wildland fire he worked in the areas of modeling turbulent combustion, microgravity combustion, and structure fires at the U.S. National Institute of Standards and Technology (NIST). His model development work occurs in close collaboration with experimentalists and modelers at the U.S. Forest Service, NIST, and academia. His current focus is on the development and testing of the wildland-urban interface fire dynamics simulator suite (WFDS). The objective of these models, and results from field and laboratory work, is to provide better tools for wildland and WUI fire researchers and guidelines for WUI homeowners, communities, and fire officials for risk assessment and mitigation. Rod Linn is a research scientist and team leader at the Earth and Environmental Science Division of the Los Alamos National Laboratory and developer of the model FIRETEC, a physics-based, coupled fire-atmospheric model.

Fire and wind interact at multiple scales, and coupled fire-atmospheric models attempt to resolve these interactions. For example, wind can be mediated by terrain, vegetation, changes in weather and fire. Fire can also influence wind through fire-front acceleration and terrain interaction (e.g., fire running up drainages), mass fires in which fire-generated winds dominate the ambient winds, and buoyancy-induced flow (e.g., plume rise due to fire-induced buoyancy).

Conventional models cannot model these processes directly and, when attempted, represent them through empirical relationships or rules based on observation. Because they simulate fundamental processes, physics-based models have broader applicability whereas empirically-based models are bounded by the limits of the original observations (e.g., Rothermel's 1972 spread model). Physics-based models can span a wide range of spatial scales because they capture the driving fundamental processes that are present at all scales. Comprehensive physics-based models explicitly model the processes of the thermal degradation of vegetation, gas phase combustion and char oxidation, smoke generation and transport, terrain influence on the ambient wind, and the interaction of the fire and surrounding atmosphere through buoyancy induced turbulent mixing. Fundamental to this is the simulation of convective and radiative heat transfer.

Coupled fire-atmospheric models apply to a broad set of disciplines and management applications including smoke generation and transport, firefighter safety, and fire effects (Mell et al. 2010b). More specifically, fire management problems that require fire-atmospheric coupled models include:

- Fire through raised fuels – buoyancy is required to carry convective heat flux upward;
- Fuel treatment effectiveness –do fuel treatments mitigate fire behavior, and can a fire jump a fuel break?
- Unsteady fire behavior – e.g., fireline acceleration up a drainage;
- Wildland urban interface – many if not most structure ignitions are from firebrands and those are transported via a plume and wind (fire-atmosphere interactions);
- Smoke generation and transport;
- Firefighter safety – primarily focused on radiation, but firefighters are also exposed to convective heat transfer; and

- Fire effects and structure ignition – e.g., heat flux from flames and firebrands, vegetation response, and interaction with vegetation structure.

It is not possible, with current computers and numerical approaches, to directly simulate all the physical processes with complete spatial resolution. A computer simulation that directly captures the first order chemical reactions of combustion requires grid cells approximately 1 mm on a side. Similarly, fire starts with ignition, which can occur at scales on the order of a millimeter. Australian grassland fires in 5 m/s winds have head fire depths of 10 m and plume rise occurs at much greater spatial scales (10's of km or greater). Ideally, a physics-based model of wildland fire would span all these scales and capture the relevant physical processes with equal physical fidelity, but computing limitations prevent this. For example, if we assume, based on our existing physics-based model, approximately 1 kB of computer memory is required for each 1 mm grid cell then a 1-m^3 domain requires 1 TB of memory, and a 10-m^3 domain requires a prohibitively large 1000 TB of memory.

The art of modeling is to determine which processes are relevant to the problem at hand and do the best job at retaining the appropriate physics. As a result, coupled fire-atmospheric models must approximate the governing equations. For example, NIST's work on faster than real time smoke transport modeling from burning oil spills on water (ALOFT; http://www.fire.nist.gov/aloft) used a fine grid resolution with simplified two-dimensional equations of motion to capture plume rise and buoyancy induced mixing. Once the plume reached its stabilization height the calculation was passed onto a coarser-grid three-dimensional dispersion model for more efficient computing of long range smoke transport.

An overview of some existing wildland fire models and their relative capability at representing wind and fire processes is provided in Figure 4. In particular, the Wildland Urban Interface Fire Dynamics Simulator (WFDS) modeling suite is able to simulate wildland and wildland-urban interface fire processes from laboratory) to landscape scales using a comprehensive physics-based approach (Mell et al. 2007, 2010a). This physics-based component of the WFDS suite is called WFDS-PB. In addition, the WFDS suite contains a simpler approach, with varying levels of physics, for simulating the propagation of the fire front. This component of the model suite is using a level set method to propagate the fire line and is called WFDS-LS. Four examples of WFDS are presented along with their computation times for simulating fire spread within a 2-km^2 WUI area, assuming for simplicity that 0.5-m tall Australian grassland fuels covers the entire domain. These examples are given to provide insight into the trade-offs in computational time and the amount of physics retained. In each case, the ambient wind speed is 14 m/s (representative of Santa Ana winds in southern California) and flows from the northwest to the southeast. While it is not the only implementation choice, the WFDS-LS model examples below use the same elliptical fire front spread assumptions found in FARSITE (Bova and Mell, 2014).

Example 1: The WFDS-LS was run with a 20-m horizontal x 3-m vertical grid was 75 times faster than real time (simulating 150 s required 2 s of CPU time on one core). The wind field was assumed to have a constant speed of 14 m/s throughout the domain and was unaffected by the terrain. This is the same assumption used in FARSITE.

Example 2: WFDS-LS model was run with the same grid resolution as in Example 1, however for this case a terrain shaped wind field was computed a-priori using WFDS-PB and used in the WFDS-LS fire front propagation model. The wind simulation added 8 minutes to the computation time (overall the computation was 3 times slower than real time). This implementation is similar in approach to using the simple wind model WindNinja (Forthofer and Butler, 2014) to provide terrain shaped winds to FARSITE (Finney 2004).

Example 3: WFDS-LS was run to propagate the fire front while coupled to the wind computation portion of WFDS-PB to obtain the local wind. The local wind field was influenced by the terrain and heat flux into the atmosphere at the fire front location. This run took 1 hour 20 minutes (32 times slower than real time). This approach of coupling a wind simulation to a simple fire front propagation model is used in the atmospheric weighted models WRF-Fire and ForeFire (see caption in Figure 4).

Example 4: WFDS-PB was run to simulate the fire spread at a 2-m resolution. Computations were 500 times slower than real time and required 128 core processors and a 30-hour run time. This simulation is the only one that provides heat flux and mass consumption information that would pertain to fire effects.

A more complex scenario was demonstrated using a LiDAR-based landscape of terrain, trees and buildings. The physics-based models WFDS and FIRETEC are both capable of doing this type of simulation (although FIRETEC cannot simulate the ignition and burning of structures). The scenario covered at 240m x 240m x 100m modeling grid with a 1-m resolution. The WFDS-PB model run was 240 times slower than real time, using 4 core processors (an 8-hr run time) for a 2-minute simulation. The example underscores the need for an experienced LiDAR analyst – for example, to distinguish between buildings and trees.

Due to computational requirements of comprehensive physic-based models, a range of fire-atmospheric models will continue to be needed for wildland fire management. Physics-based models are useful as research tools but also have proven capability for application and are needed to support the development and testing of simpler tools. Major needs include advances in computational efficiency and more supporting measurements for sub-model parameterization and validation. Measurements are needed at both the laboratory and field scale. Laboratory-scale measurements, due to their measurable uncertainty, can be used to develop and assess sub-models with a comprehensive physics-based approach (e.g., role of moisture, live versus dead fuels, char oxidation, smoke production). Field-scale measurements are needed in order to test the ability of models tested and developed at laboratory scales to “scale-up” to field scenarios. Also, it is not feasible to test the range of relevant parameter values in the laboratory, especially for large fires, high winds, and complex fuels. Suites of models are needed with physics-based models to inform solutions within faster operational models.

Wind Model / Fire Model	Uniform wind	Terrain shaped wind	Vegetation shaped wind
No explicit fire	CA models Farsite Prometheus WFDS-LS	Farsite & WindNinja Prometheus & WindNinja WFDS-LS	WFDS-LS
Simplified heat injection (buoyancy induced flow)		WRF-Fire, ForeFire WFDS-LS	WFDS-LS
Combustion (buoyancy, heat transfer, vegetation degradation)		FIRELES FIRESTAR FIRETEC WFDS-PB	

Figure 4: Overview of some existing wildland fire models and their capability including cellular automaton (CA) models, FARSITE (Finney 2004), Promethius (http://www.firegrowthmodel.ca),WFDS-LS (WFDS level set; https://sites.google.com/site/wuifiresfiremodels), WindNinja ((http://www.firelab.org/research-projects/physical-fire/145-windninja), WRF-Fire (http://www.openwfm.org/wiki/WRF-Fire), ForeFire (http://forefire.univ-corse.fr), FIRELES (Tachajapong et al. 2008), FIRESTAR (Morvan et al. 2009), FIRETEC (Linn et al. 2002), and WFDS-PB (Mell et al. 2007and https://sites.google.com/site/wuifiresfiremodels).

For model validation, experimentalists and modelers need to work together in order to ensure that the relevant measurements are taken and the actual experimental procedure and configuration is modeled. It will be important to characterize model limitations over a range of relevant scales and scenarios. Specific needs for laboratory studies include 1) momentum drag in vegetation, 2) radiant absorption by vegetation, 3) thermal degradation of vegetation types including live and dead vegetation, 4) heat release rates by vegetation type, and 5) experiments that enable laboratory-to-field extrapolation (e.g., fireline acceleration).

Needs for field measurements include: 1) time evolution and dimension for the entire fire line perimeter and its depth, 2) measured heat flux, 3) smoke plume concentration, rise and height, 4) vegetation size class distribution and mass in pre- and post-fire conditions, 5) wind including near-ground and far field around experimental burn plots and influences of terrain and vegetation on wind, 6) firebrand production and deposition, and 7) experiments on fuel break effectiveness.

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7. Craig Clements, State of Fire-Atmosphere Interactions Research: smoke and fire behavior modeling

Author Bio: Craig Clements is an Associate Professor of Meteorology and director of the Fire Weather Reserach Laboratory at San Jose State University. His research interests include micro-meteorology and behavior of wildland fires, mountain and boundary-layer meteorology, air pollution and turbulence.

Fire-atmosphere interactions (FAI) are defined as the interactions between presently-burning fuels and the atmosphere in addition to interactions between fuels that will eventually burn in a given fire and the atmosphere (Potter 2012a). The duration of FAI is considered to be as long as fire-induced perturbations are greater than ambient variability. In other words, FAI is the coupling of the fire and the atmosphere and feedback mechanisms between the two. Potter (2012a and b) provided a review of historic FAI research and summarized five research goals in FAI research and provided recommendations for future research directions. FAI information gaps can be organized into five main categories including 1) atmosphere vertical structure and the role of stability on fire spread, 2) vertical wind profiles, 3) plume dynamics, 4) wind and fire-front dynamics, and 5) micrometeorology and turbulence.

1) Temperature profiles and atmospheric stability. To gain a better understanding of temperature structure of plumes and effects on fire behavior, some of the key research areas include the rate of entrainment in a rising plume, the degree to which energy is released by a fire and how that translates into kinetic energy of the updraft, and how stability profiles influence updrafts including the relative influence of horizontal convergence, divergence and fire intensity.

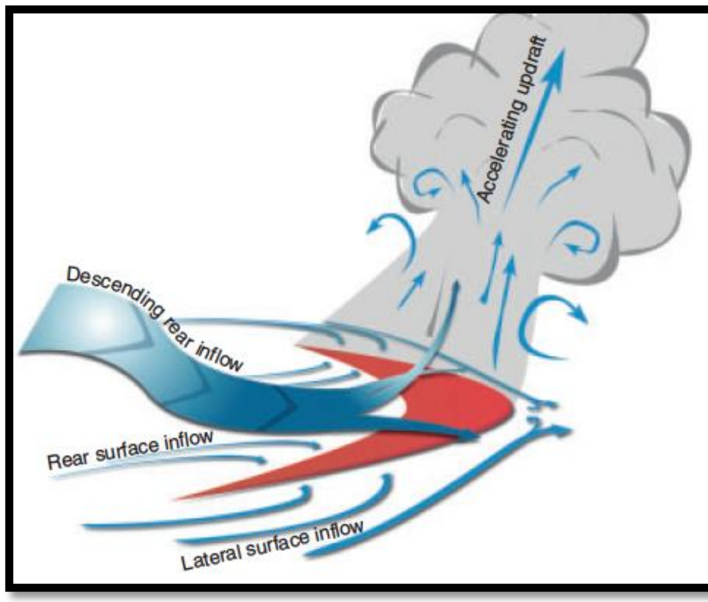

Figure 5: Conceptual diagram of airflow in and around a developed fire front (Potter et al. 2012b).

2) Research on vertical wind profiles is needed to inform fire behavior and atmospheric modeling. In particular, information is needed on boundary layer mixing of winds aloft down to the surface including vertical shear and the development of fire whirls. Preliminary research on vertical wind shear profiles was conducted by Byram (1954). A recent numerical model of differing wind shear profiles and fire behavior impacts was published by Konchanski et al. (2013). Research on wind profiles is rooted in basic meteorology and requires further understanding of how boundary layer mixing of winds aloft down to the surface influence fire behavior (e.g., development of fire whirls).

3) Plume dynamics are not well understood including inflows (lateral surface, rear surface, descending rear) as well as accelerating updraft (Potter 2012a, b)(Figure 5). Key research questions include:
   - What factors influence the origin of inflow? Standard measurements of sensible heat flux are needed in particular.
   - How would incorporation of descending inflow affect fire spread?

4) Wind and fire-front dynamics. One of the key questions is what is the most pertinent measure of wind speed (i.e., surface, mid-flame and upper level) in predicting rate of fire spread? Empirical studies have shown a weak correlation between spread rate and wind speed (Cheney et al. 1993, Potter 2012a,b). High resolution wind profiles are still missing in validation datasets.

5) Micrometeorology and turbulence. There are few measurements on the effects of fire-induced turbulence on fire spread, but Taylor et al (1973) suggests that variability of fire-induced winds plays a role. Sun et al. (2009) also suggest that boundary layer turbulence is an important factor in fire spread. Key research questions include:
   - What role does ambient turbulence have on fire spread and smoke, dispersion and fire-front properties?
   - How does fire intensity affect turbulence structures?
   - A better understanding of fire front properties and sensible heat flux is also needed.

Technological developments have allowed for a wide range of new measurements to be made in FAI studies. In-situ meteorological measurements are one of the most important aspects of new field studies such as FireFlux and Fire Flux II (Filippi et al. 2013, Konchanski et al. 2013), sub-canopy (Strand et al. 2013) and the 2012 RxCadre experiments (http://www.firelab.org/research-projects/physical-fire/205-rxcadre). Measured data can be used to 1) quantify FAIs and their role on fire behavior, 2) evaluate coupled-fire model simulations and 3) determine the impact of meteorology on fire behavior, emissions and smoke transport. For example, the Fire Weather Research Laboratory (San Jose State University, CA) has a mobile atmospheric profiling station (CSU-MAPS) that includes a Halo-scanning Doppler LiDAR (Charland and Clements 2013), radiometric microwave temperature/relative humidity profiler, Vaisala MW31 Radiosonde System, and a surface weather station.

Micrometeorology of the fire-front passage (FFP) can now be quantified by measuring surface wind reversal, peaks in turbulence via sensible heat flux, and atmospheric pressure minimum values. The relative strength of each variable determines fire-atmospheric coupling. An example experiment is FireFlux II (Jan 30, 2013) which characterized turbulence spectra using wind directions, vertical velocity and temperature profiles during pre-, during, and post-periods of the fire-front passage. Spectra were calculated every 30 minutes, which allowed characterization of normalized (ambient) turbulence spectra (Seto et al. 2013) during and post fire-front passage. The study detected an increase in velocity spectra at higher frequencies due to shedding of small-scale eddies from fire front. RxCadre compared vertical and horizontal velocity turbulence spectra in RxCadre and FIreFlux2. Turbulence spectra were very similar between the two studies, and even low intensity fires (e.g., in RxCadre fires) have increased turbulent energy at high frequencies.

Microwave radiometer T/RH measurements have shown promising results. In one example, a start of a cold/dry front was detected by a drop of relative humidity just before a burn unit was successfully ignited. Scanning Doppler wind LiDAR has also been successfully used to characterize plume development using a 1.5-µm laser. However, better resolution is needed for three-dimensional characterization and would require at least dual Doppler measurements to fully characterize plume structure. Fire whirl observations have also been made.

In summary, reliable observations are needed to test theories and validate FAI models at micro- to mesoscales. In-situ monitoring is now possible with available technologies and offers promising advances in observations to inform fire behavior modeling. Some key measurement needs include 1) dual or tri-Doppler LiDAR measurement strategies for plume dynamics and wind field monitoring (e.g., real time, three-dimensional wind profiles), 2) coupled LiDAR with in-situ towers to generate composite wind and turbulence field analyses, and 3) fire behavior measurements at high temporal and spatial resolution simultaneous with FAI measurements.

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8. Kevin Hiers, Application of Fire Behavior Models to Ecosystem Management

Author Bio: J. Kevin Hiers is the acting chief of the Air force Wildland Fire Center.

Forest managers are faced with managing ecosystems under a future with no analogues. Climate change and invasive species including pests and diseases have altered vegetation dynamics, creating novel ecosystems and disturbance regimes. A critical challenge for managers is to change a fundamental approach to ecosystem management. Ecological managers generally work under an adaptive management strategy, using past experience to guide future decisions and strategies. Although variability is inherent in fire management, prescriptions around mean historic conditions are meaningless under a no-analogue future. For example, managing for a specific structure (e.g., historic fuel loads or stand densities) may not ensure a viable future for some ecosystems (e.g., long leaf pine ecosystems). Similarly, fire and fuels managers have generally characterized historic fire regimes and used historic conditions as restoration targets. However, we can expect more wildland fires to occur out of perceived or historic norms.

Variability is inherent in fire management, and under a changing climate, predictions around mean conditions will be meaningless. Future fire management must be able to capture relevant or anticipated variability with physics-based models of fire behavior. Forest fire research has traditionally had two very separate disciplines of physical sciences (combustion, heat) and ecological sciences (foresters, ecologists, fire effects). Fuels are the connection between the two formerly disparate disciplines.

Because we can no longer use the past to anticipate the future, ecological models need to couple physics-based fire models with vegetation change. Empirical models will not work for a no-analog future. More specifically, to capture fine- to- large-scale variation relevant to fire effects, process-based ecosystem models need to be coupled with mechanistic ecosystem disturbance models including physics-based fire behavior predictions that simulate both fine- and coarse-scale fire dynamics. Next-generation models should be useful to identify thresholds of ecological response (i.e., tipping points) through simulations under ranges of potential climatic and vegetation change scenarios.

There are several challenges to process-based ecosystem modeling:

1) Carbon dynamics operate on a range of intersecting scales and are difficult to quantify and track;
2) Ecosystem modelers encounter scaling issues (e.g., from the scale of a leaf to forest stands to landscapes) that are difficult to reconcile;
3) Co-limitations of resources (N, P, water, light) complicate ecological responses and are difficult to model; and
4) Currently, disturbance regimes are generally represented by other models and are not well integrated into process-based ecosystem models.

A range of process-based ecosystem models exist, but it is challenging for managers to select which models to use based on represented scales, data requirements, species representation and how disturbance regimes are incorporated. Some examples of process-based ecosystem models include:

- The Soil-Plant-Atmosphere (SPA) model models photosynthesis and water balance at fine spatial and temporal scales across canopy and soil layers (Williams 1996; http://www.geos.ed.ac.uk/homes/mwilliam/spa.html).
- BGV
- The Data Assimilation Linked Ecosystem Carbon (DALEC) model simulates landscape carbon dynamics (Williams et al. 2005).
- The CENTURY ecosystem process model simulates soil organic matter and plant production dynamics (Parton et al. 1987, 1988). It was originally developed for grassland and agricultural systems but has also been applied to study biogeochemical cycling in forest ecosystems and has been applied to climate change studies (Schimel et al. 1991).
- The Regional Hydro-Ecologic Simulation System (RHYESSy; http://fiesta.bren.ucsb.edu/~rhessys) is a geospatial modeling framework that simulates carbon, water and nutrient fluxes (Tague et al. 2004) and has been widely used for climate change modeling (Tague and Dugger 2010).

Future models need to articulate limits to model application (domains of inference) and identify uncertainty at operational and planning scales. For this, we need long-term datasets to monitor and validate predictions. To assist managers in model selection, inter-model comparisons using common datasets will be important. Linking ecosystem process-based models with mechanistic disturbance models will be critical for managers under a changing climate. A conceptual model of a unified model for prescribed fire is presented in Figure 6.

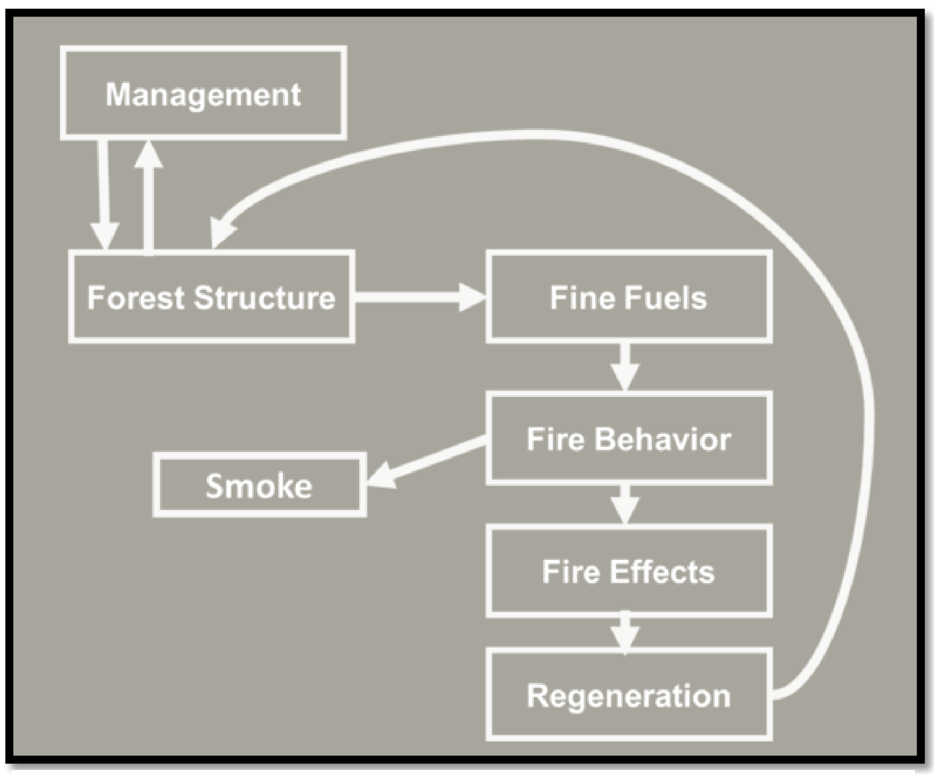

Figure 6: A conceptual diagram of a unified model for prescribed fire, including fire behavior, effects, and vegetation dynamics (adapted from Joe O'Brien).

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9. Matt Dickinson*, Tony Bova and Joe O'Brien, Trends and Major Gaps in Fire Effects Research and Development

Author Bio: Matt Dickinson is a Research Ecologists with the Northern and Southern Research Stations. Matt is a research scientist on the RxCADRE project, focusing on ground and airborne monitoring of fire behavior and effects. He has also collaborated on projects modeling the processes that govern fire effects such as tree and faunal injury and mortality.

Introduction

Advances in fire behavior science will facilitate advances in fire effects science as fire behavior predictions and fire effects models become more physically realistic. This trend will have most immediate consequences for what are termed first-order fire effects, effects that happen as a direct result of flame and plume behavior. I will illustrate the benefits arising from increasingly mechanistic fire models with recent examples from the literature. As well, I will provide an assessment of trends and gaps in fire effects science from recent reviews that take a broader view of fire effects science by including second-order effects, tools for fuel treatment and prescribed fire planning, and risk-based wildfire management. A conceptual diagram of the links and feedbacks between fire and its effects are shown in Figure 7.

How mechanistic fire behavior science benefits fire effects science (and vice versa)

Before showing how fire effects science advances with fire behavior sciences, one may ask, why is development of mechanistic fire effects models important? Apart from an improved ability to make use of advances in fire behavior models, more process-based effects models lead to advances in understanding. For instance, a recent hypothesis of canopy injury is that heat alone does not cause "crown scorch", a ubiquitous fire effect. Rather, the sudden and pronounced drying of the atmosphere in fire plumes increases water column tension to the point where it can cause cavitation in the vessels of foliage and branches with varying effects among species (Kavanagh et al 2010). Cavitation in branches often is expected before heat injury can occur, but this result must be further explored for foliage, which is generally expected to be more vulnerable to cavitation than branches. This example illustrates how even common fire effects can be misunderstood without a good understanding of underlying mechanisms. Misunderstanding of mechanisms then results in misleading predictive models. Fire behavior models are increasingly mechanistic. With the advent of gridded coupled fire-atmosphere models, fire behavior predictions respond realistically to variability in fuels, vegetation structure and meteorological conditions (see Mell, this report). With these new capabilities, we can study spatially-explicit boundary conditions for fire effects. A growing number of fire effects studies are using fire-atmosphere models to examine variation in fuel/vegetation structure and to quantify boundary conditions and provide inputs to fire effects models. For example:

1) Bova et al. (2011) used WFDS to evaluate boundary conditions for gas mixing into cavities used by fauna. The two critical variables are gas temperature and carbon monoxide,

representing the most significant ways animals can be harmed by fire in a cavity. Applications can be extended to unsheltered fauna such as bats (Dickinson et al. 2010).

2) The stem heating model FireStem was just updated to model boundary conditions of uneven stem heating (Chatziefstratiou 2013). Work is in progress by Bova et al. to validate the use of the coupled fire-atmosphere model WFDS (see Mell, this report) as a means of generating stem heat flux inputs to FireStem (now called FireStem 2D).

3) Hoffman, Battaglia and Ziegler (in prep) are using WFDS to evaluate the effects of canopy fuel treatments on canopy turbulence and fire spread. The study demonstrated a high variability in turbulence and nonlinear effects on rate of spread.

4) Michaletz et al. (2013) used the WFDS model (see Mell, this report) to generate boundary conditions for a white-spruce cone heating model. Results suggested that this non-serotinous species could often regenerate effectively after crown fires because viable seeds in cones survived heating.

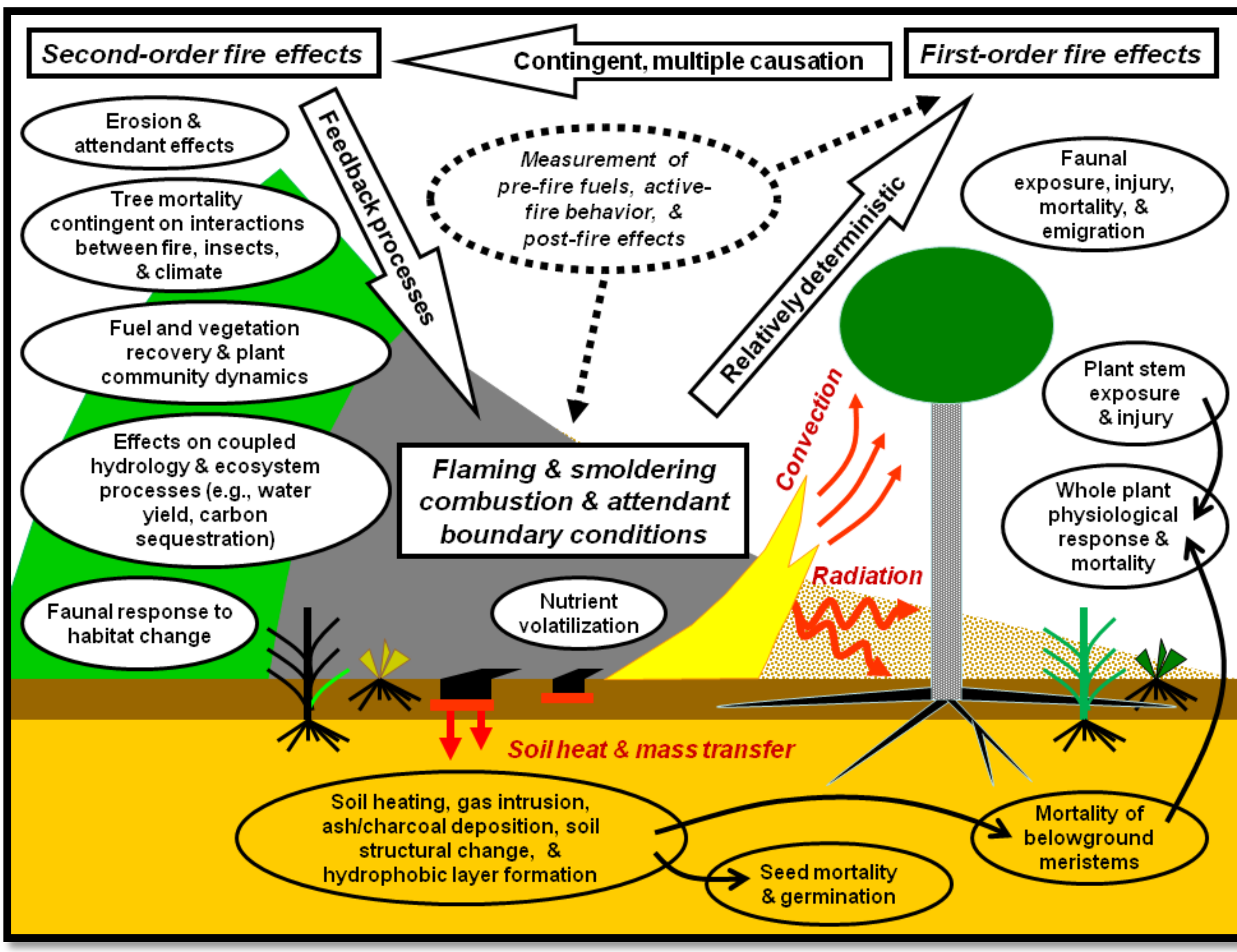

Figure 7. Fire effects science involves linking fire behavior with relatively direct (first-order) effects and first-order effects with longer-term (second-order) effects that, in turn, feed back on fire dynamics through fuel and stand conditions.

One may ask, how practical is using complicated physics-based models in fuel treatment and prescribed fire planning and fire management applications? More mechanistic models take longer to run, often at speeds slower than real time. A solution to this problem lies in the definition and use of functional relationships or look-up tables developed from the output of computationally-intensive models such as WFDS and FireSTem2D. These lookup tables can then provide inputs required by effects models.

Current operational fire behavior models (most based on the Rothermel [1972] model), unlike more mechanistic fire models, do not generally provide the boundary conditions needed by new fire effects models. Consequently, a key research need is to develop the means by which boundary conditions that link fire behavior with effects can be obtained. As an example, Bova and Dickinson (2008) demonstrated how basic fire behavior information, like rate of spread, fire intensity, and flame dimensions, variables that can be derived from Rothermel-based models, could be used to generate radiation and conduction boundary conditions for thermocouple probes heated in fires. This approach could be adapted to provide boundary conditions for predicting soil and tree heating in fires.

Recent reviews of fire effects science and its application to fuels and fire management

We have described in the preceding how improvements in fire behavior modeling will have broad benefits, including a better understanding of direct fire effects. In the following, we take a broader view of fire effects science, summarizing results of recent reviews of the field.

Fire Ecology special issue (2010)

Seven papers in this special issue focus on the development of first-order fire effects predictive capacity and application of effects models to fuels treatment and prescribed-fire planning. The focus is particularly on mechanistic (process-based) models. Table 4 provides a list of key research and development needs in the areas of fire behavior and fire effects measurement ("metrology"), soil heating, tree injury and mortality, fire effects on shrubs and herbaceous plants, and fire effects on fauna. A final paper (Reinhardt and Dickinson 2010) describes key trends, including the rise of one-stop-shops for data and models (e.g., the Integrated Fuel Treatment Decision Support System [IFT-DSS] and the Wildland Fire Decision Support System [WFDSS]) and development of the capability to make ensemble predictions from alternative models (IFT-DSS). Dickinson and Ryan (2010), in the introduction, offer the following challenge to the research community: the development of a comprehensive, first-order fire effects model employing a diversity of approaches (from statistical to process) and built to serve a range of applications (from research to land management).

Table 4. Papers in the 2010 Fire Ecology special issue and the main gaps they identify in process modeling and measurement capabilities and in model application to land management.

Author(s)	Title	Key Research and Development Needs
Kremens *et al.* (2010)	Fire metrology: current and future directions in physics-based measurements	Development of ground-based LiDAR fuel sampling techniques, application of airborne fire radiation mapping to a range of ecosystems, critical examination of satellite-based "fire severity" measurements.
Massman *et al. (2010)*	Advancing investigation and physical modeling of first-order fire effects on soils	Models for predicting soil-surface boundary conditions from smoldering and flaming combustion and the inclusion of pressure-driven advective flows as well as heating-related dynamic feedbacks in soil heating models.
Butler & Dickinson (2010)	Tree injury and mortality in fires – developing process-based models	The ability to predict the boundary conditions that drive soil and tree heating, greater knowledge of tree thermal and physical characteristics, a linking of statistical and process approaches for predicting tree mortality.
Kavanagh *et al.* (2010	A way forward for fire-caused tree mortality prediction: modeling a physiological consequence of fire	High vapor pressure deficits in the plume may cause unappreciated impairment to trees' water conducting systems which may cause either outright mortality or loss in productivity. A better understanding is needed of the physiological responses of trees to fire exposures and their role in both causing tree death directly and increasing tree vulnerability to other stressors (e.g., drought, insect attack).
Stephan *et al. (2010)*	First-order fire effects on herbs and shrubs: present knowledge and process modeling needs	The belowground distribution and responses of bud and seed populations to fire are poorly known. Predictions of subsurface mortality are uncertain because of a limited ability to characterize the soil surface boundary conditions that drive soil heating, a problem arising from both a poor knowledge of the spatial arrangement of fuels and inadequacies in flaming and smoldering combustion models.
Engstrom (2010)	First-order fire effects on animals: review and recommendations	Effects of fire on faunal habitats are generally seen to be more important than direct effects, though data are lacking. Species-Centered Environmental Analysis is presented as a means of defining key effects on habitats that can serve as targets for first-order fire effects modeling.
Reinhardt & Dickinson (2010)	First-order fire effects models for land management: overview and issues	Software systems under development for use by land managers are built on a foundation of predictive fire effects models that suffer from the weaknesses discussed in this special issue.

Hyde et al (2013)

A recent synthesis article was published by Hyde et al. (2013) in a JFSP special issue in the International Journal of Wildland Fire. Building on the 2010 Fire Ecology special issue, which focused primarily on first-order fire effects, the paper also considered second-order effects and risk-based decision making in fuels and wildfire management. Table 5 lists research needs in the areas of fire behavior, first- and second-order fire effects, spatial and temporal integration, and application to management.

Table 5: Summary of research needs for development of risk-based fuels and wildfire management decision-support systems.

Component	**Research needs**
Fire behavior	• Provide fire model outputs relevant to fire effects prediction • Improve process-based fire models including geographically extensive validation • Improve model input data, e.g., fuels and meteorology
Fire effects – 1st order	• Process couplings between fire behavior and fire effects • Develop fire effects prediction in herbaceous and shrub vegetation • Knowledge of soil-surface heat fluxes, physiological basis for tree injury
Fire effects – 2nd order	• Improve access to and organization of fire effects literature • Clarify relationship between vegetation change and post-fire erosion • Changes in sediment flux, biogeochemical cycling, and nutrient/constituent export • Couple forest regeneration models with models of fire effects • Develop process-based habitat suitability models with targets linked to fire effects
Spatial and temporal integration	• Spatial interactions over time, accounting for system recovery • Cross-scale analysis over full range of fire effects interactions • Assess wildfire disturbance and response relative to other disturbance processes
Risk framework	• Methods to quantify expected value change, especially for non-market resources • Develop probability assessment techniques accounting for wildfire complexities • Build seamless, interactive decision support systems with efficient data management

Conclusions

- Fire effects science is becoming increasingly mechanistic, leading to improved predictive capabilities and understanding. Process-based fire effects science has and will benefit from advances in physics-based fire science.

- Fire science and fire effects science will both benefit from improvements in both fire measurement science (i.e., fire metrology) and predictive infrastructure (i.e., the availability of model input variables such as fire weather, fuel moisture, and fuel and stand structure at appropriate spatial and temporal scales).
- Improvements in first-order fire effects science will result in improved prediction of second-order (longer-term) fire effects and those improvements will result in improved predictions of fire behavior and, in turn, first-order fire effects.
- Fire effects science supports development of risk-based decision-support systems for fuels and fire management.

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Afternoon Session Q&A

Q1 (Jacob Wolf, air quality meteorologist, Idaho Department of Environmental Quality for Craig Clements): What differences have been observed within the passage of the fire frontal boundary between rangeland fires such as the Texas experiment versus timber fires?
Craig Clements: Generally, if you're talking about surface fires in the forests, the wind flows are slower due to canopy effects, so fire behavior is slower although there are higher fuel loads. Whereas in open rangeland, you have higher surface winds so that there are higher spread rates on the surface. We have not made those comparisons yet but we do have the data.

Q2 (John Hall): How important is it to go beyond the single plume characterization to multiple plumes that may have interaction effects? The only model I am aware of that does this is DaySmoke.
Craig Clements: there have been a couple of studies on this. I think there is a lot of interaction. Even within simple prescribed fires, there can be multiple convective cores. How they interact, we can only speculate. We haven't done any quantitative analysis from RxCadre.

Q3 (John Hall) – but do you think it's something we should think about?
Craig Clements: Yes. It would be hard to do this ground-based, but if you have multiple scanning LiDAR, you can capture them all.

Q4 (Marty Alexander for Kevin): How confident are you in the research community that predictive models will deliver? Should we not be advising managers to be practicing adapted management?
Kevin Hiers: These modeling tools are going to help us address uncertainty as a principle character of adaptive management. We really need to become practitioners of adaptive management and be humbled by what we do not know. I do believe the ecological modeling community is poised to help out in a planning sense, but we need new frameworks as managers for long-term planning.

Discussion:
Kevin Hiers: There seems to be a dynamic tension between the need for more targeted campaigns for specific questions versus more comprehensive campaigns.

Unknown participant: Archiving data and storing it will be important for helping to address questions that we may have in the future.

Roger Ottmar: one of the critical things that the JFSP requested was a data management plan. First, they wanted to have a dataset where all participants could post and share. Second, they needed to find a central repository for the public to access once the dataset is approved for dissemination. Metadata and project documentation were also required.

Kevin Hiers: It would be worthwhile in investing in archival efforts to other projects. If we are going to try to build a comprehensive dataset, RxCadre is just one example.

Unknown participant: NSF requires a data management plan and requires data be released within 3 years for other purposes.

Kevin Hiers: One point that Al Riebau brought up was would an artificial, common dataset from perhaps a series of modeled ecosystems a valuable next step to evaluate the performance of a variety of different tools?

Ruddy Mell: Yes. All models need to have standardized tests. That is not available right now.

Colin Hardy: Russ Parsons and Chad Hoffman have developed stands through Fuels3D that they have run through WFDS and FireTec. One of Russ Parson's objectives was that synthetic stands could also represent shade and insolation for growth models.

Ruddy Mell: Russ has JFSP funding to do stand-level comparisons, but much more should be done for a canonical test bed.

Mark Dietenburger: I heard no mention of moisture transport as affecting FAI.

Craig Clements: They have made a number of measurements of water vapor from fires. There is a debate right now about sensible heat flux versus latent heat flux and if water vapor is really important. I didn't mention it in my talk, but we do have some measurements, and it's an ongoing research problem.

Marty Alexander – Kevin, can the US government afford to continue carrying out expensive experiments such as RxCadre?
Kevin Hiers: I think that's one of the reasons why we are here to figure out the next investment priority and what is the return on our past investments.

Craig Clements: Millions of dollars were spent on Vortex II to measure tornados. The funding was high risk because sometimes the weather doesn't cooperate.

Kevin Hiers: A prescribed fire planned event will always be more cost effective versus rapid response. If I were going after a rapid response, it would be for very specific study objectives.

Roger Ottmar: A critical advantage of RxCadre is that we pulled in a tremendous number of scientists. This increases efficiency and facilitates data sharing. It was extremely effective.

Kevin Hiers: Do we really need a series of field campaigns for a targeted purpose? Meeting all of the fire behavior and effects objectives wasn't possible because of the different scales involved. Planning for those different scales and objectives should be considered in the next field campaign.

John Hall: Project leveraging may be possible. For example, the FireTec validation project is making use of the RxCadre dataset. Broad communication to the research community ahead of time may help us to be strategic in data collection and to allow for multiple funding sources.

Colin Hardy: Suggested that the questions be the criteria for who is involved. Colin recommended that any team really uses the research questions as the triage rather than the people and the measurements.

Kevin Hiers: One tradeoff that we have to battle is how much value do we get from these field campaigns? If data collection is compromised for specific applications, we may not be getting any significant advancement to science. Kevin would be interested in more comprehensive thoughts on what the validation datasets would be for the next 30 years. What do we need so that we can build the field campaigns to build standards for synthetic data standards?

Matt Dickinson: Almost after the fact, RxCadre got JFSP funding to develop datasets, but in a future proposal we need to ensure that the people that are going to use the data are there at the start of project design.

Conclusions – key research/demonstration gaps

The following are key research and demonstration gaps synthesized from the special session on ***State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues*** that may be of relevance to SERDP/ESTCP or of interest to the Department of Defense:

Fuel characterization and consumption

- For wildland fire emissions and carbon accounting, improved characterization and mapping of fuels is needed that accounts for all fuelbed components from canopy to surface fuels and characterizes diverse fuel complexes (e.g., masticated fuels, homes and landscapes within the wildland-urban interface, and invasive species assemblages). To address this, evaluation of new, spatially explicit fuel measuring protocols and tools (e.g., LiDAR and SAR) is needed with field sampling verification. Development of a central data repository for fuel datasets would also benefit fuel consumption and fire behavior modeling efforts.
- Improved post-fire consumption estimates are also needed for wildland fire emissions and carbon accounting, including systematic measurements of fuel consumption by fuelbed component (e.g., shrubs, herbaceous fuels, woody fuels by size class, litter and duff) and combustion phase over a range of fuel moisture and other environmental conditions. Integrated approaches using field and laboratory sampling, remotely sensed data, and physics-based models that resolve fuel combustion would be particularly useful.

Smoke and plume dispersion modeling

- Develop and improve smoke and plume dispersion models. Recent technological advances will allow for significantly better smoke forecasting systems with improvements in fire growth modeling for area burned and diurnal timing, coupled dynamic plume rise modeling for better injection, and improved understanding of plume chemistry. We also need to address 1) better utility, accuracy, and timeliness of model inputs and outputs, 2) smoke dispersion, 3) meteorology, 4) fuel characteristics, 5) improved initialization process modeling, and 6) improved interpretation capabilities. A key challenge will be to collect validation data in order to support development of these next-generation models.
- Design and execute field experiments to validate next-generation smoke models. This will require field experiment partnerships and validation criteria and an increased focus on heavy fuels and high-intensity fire events. Experimentalists and modelers need to work together to inform validation studies, new measurements, and model refinement through iterative testing and modification. Variables to model and test include 1) fire growth and behavior, 2) fuel consumption, 3) influence of fuel moisture on combustion, 4) plume structure and transport, and 5) ground smoke impacts.

Fire behavior modeling

- Improve model validation, testing, and identification of uncertainties of physics-based fire behavior and effects models. Specifically, we need to improve our understanding of why fires spread or don't spread, including relationships between fire spread and wind speed and moisture conditions and mechanics that drive fire brands (generation, transport and ignition). This will require laboratory work and field confirmation. Issues of scaling from laboratory to field observations are complex. Fire behavior models need to be tested across multiple scales, and it will be important to characterize model limitations across a range of relevant scales and scenarios. Common datasets are needed to allow cross-model comparisons at different scales. To ensure consistency, synthetic datasets may be useful. Standards for comprehensive validation datasets are needed to inform future field campaigns and/or the development of synthetic datasets.

Fire-atmosphere interactions

- Improve our understanding of fire-atmosphere interactions including 1) vertical temperature and wind profiles, 2) plume dynamics, 3) wind and fire front dynamics, and 4) micrometeorology including turbulence. Develop new uses of LiDAR including dual or tri-Doppler LiDAR measurement strategies for plume dynamics and wind field monitoring. Coupled LiDAR with in-situ towers can be used to generate composite wind and turbulence field analyses.

Climatic change and ecosystem modeling

- Evaluate plausible future climate change scenarios and no analog, novel, and disappearing climates and their implications for fire and ecosystem-based management. To anticipate a range of outcomes and possible threshold effects under climatic change scenarios, ecosystem process models will need to directly incorporate disturbance models. Coupled physics-based fire behavior models will need to be merged with ecological effects process models. Some of the challenges will be to: 1) articulate model domain of inference, 2) explicitly characterize uncertainties, 3) validate models with long-term data sets, and 4) conduct inter-comparisons among different models against common data sets.
- Large, integrated science assessments are needed for climate change, regional assessments, and model validation and will require coordination to leverage funding to support them through shared funding and research projects.

Fire effects science

- Fire effects science is becoming increasingly mechanistic, leading to improved predictive capabilities and understanding. Process-based fire effects science has and will continue to benefit from advances in physics-based fire science. Fire behavior and fire effects disciplines will both benefit from improvements in fire measurements and predictive infrastructure (i.e., the availability of model input variables such as fire weather, fuel moisture, and fuel and stand structure at appropriate spatial and temporal scales).

- Studies are needed to parameterize fire effects models with next-generation, physics-based fire behavior models including boundary conditions and realistic fire behavior in structurally heterogeneous fuels, changes in forest structure from surface and canopy fuel treatments, and changes in meteorological conditions. Improvements in first-order fire effects science will result in improved prediction of second-order (longer-term) fire effects and those improvements will result in improved predictions of fire behavior and, in turn, first-order fire effects.

SPECIAL SESSION ABSTRACTS

State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues

The Strategic Environmental Research and Development Program (SERDP) in conjunction with the Joint Fire Science Program and Core Fire Science Caucus will host a special session at the 2013 International Smoke Symposium to identify research gaps associated with the integration of fire behavior modeling, smoke dispersion modeling, emissions production, coupled fire-atmospheric dynamics, and fire effects as they relate to ecosystem and smoke management issues. As a result, the purpose of the session will be to broadly highlight the state of the science of these interdisciplinary topics and identify research and model validation gaps. An additional focus will be on integrating these core fire science gaps to model critical fire effects and understand landscape ecosystem processes.

SERDP's Resource Conservation and Climate Change program area funds research priorities for the Department of Defense related to ecological forestry and the air quality and management aspects of fire (http://www.serdp-estcp.org/Program-Areas/Resource-Conservation-and-Climate-Change). The Joint Fire Science Program is a national, interagency wildland fire science funding program with long-term interests in smoke, fire behavior, and fire effects models (www.firescience.gov). The Core Fire Science Caucus is an ad-hoc open body of researchers in the fields of combustion physics, wildland fuels, and coupled fire-atmospheric feedbacks. Its history of collaborative efforts in smoke and fire science offers a constructive, open forum to explore the strategic research needs for smoke, combustion, and coupled fire-atmospheric interactions.

Speakers will present on the state of the science in a variety of interrelated disciplines, but each talk will be structured to maximize discussion and exchange of ideas. The final talk will highlight and synthesize the challenges of integrating the physics of fire behavior and effects with atmospheric science in next generation modeling tools and also identify key research gaps. As part of the symposium proceedings, a summary of research gaps and model validation needs will be produced from the discussions.

1) **John A. Hall – Overview of funding sources SERDP/ESTCP and JFSP and their research/demonstration priorities**

Fire plays a vital role in the ecology of fire-adapted ecosystems and, due mostly to the introduction of non-native invasive species, in non-fire-adapted ecosystems as well. The Department of Defense (DoD) manages both types of ecosystems. In forest ecosystems, use of prescribed fire is an integral part of the silvicultural prescription toolbox associated with ecological forestry. To support DoD's continued use of fire as a management tool, the Strategic Environmental and Research Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) fund efforts to address both characterizing emissions associated with fire to meet air quality requirements and understanding how fire acts as a disturbance process that resets ecological communities of management concern to DoD. Emerging needs include carbon accounting in fire-adapted ecosystems and trade-offs with other ecosystem services, a more fundamental understanding of how fire behavior affects ecosystem and smoke management issues, and fire behavior and other model validations. To assist in providing direction to its research and demonstration efforts, in coordination with the rest of the fire science community, SERDP/ESTCP is developing a fire science plan. The conceptual model that provide a strategic basis for this plan is organized around five focal areas of research/demonstration that support DoD needs and provide avenues for collaboration with other agencies interested in advancing fire science: (1) fire behavior, (2) ecological effects of fire, (3) carbon accounting, (4) emissions characterization, and (5) fire plume dispersion.

2) Roger Ottmar*, Carl Selestad, Clint Wright, Susan Prichard - State of fuel characterization and consumption for wildland fire planning

Wildland fuelbeds are composed of fuel particles derived from live and dead plant parts. The physical and chemical characteristics, amount, arrangement, continuity, and condition of those particles, in addition to topography and weather influence how much, and which parts, of a fuelbed will combust and consume during wildland fires. During the past 40 years, great strides have been made toward characterizing fuels before and after wildland fire to support fire models that predict fire behavior, fuel consumption, fire effects, and smoke production. This has led to the development and improvement of protocols and tools to characterize fuels such as the planar intercept inventory method, fuel type-specific allometric equations, natural and activity fuel photo series, Fire Effects Monitoring and Inventory System (FIREMON), Fuel Loading Models (FLM), Fuel Characteristic Classification System (FCCS), and aerial and terrestrial LiDAR. As the need for fuels data increases in complexity, however, these protocols and tools will soon prove to be inadequate, requiring new and innovative approaches to better capture the structural and chemical complexity, and spatial diversity of pre- and post-fire fuel. For example, The Wildland–urban Interface Fire Dynamics Simulator (WFDS) requires explicit surface area-to-volume ratio and bulk density properties of each fuelbed layer. These variables are difficult to measure in the field with current inventory methodologies but new approaches using terrestrial LiDAR and three dimensional fuel modeling show promise for addressing this need. In addition, a variety of important fuelbed types and categories are poorly characterized with current systems and protocols, including wetlands, invasive species, masticated fuels, tree and shrub crowns, rotten logs, and below ground biomass. This presentation will begin by reviewing the past and present state of characterizing fuels and important knowledge gaps, and conclude with a discussion of innovative ways to close these gaps as we move forward in building a solid science foundation for improved understanding and prediction of fire behavior, fire effects, and smoke production from wildland fire.

3) Narasimhan K. Larkin*, Susan O'Neill, Sean Raffuse, Miriam Rorig, Robert Solomon, Tara Strand, Tim Brown, Roger Ottmar, Pete Lahm – State of smoke dispersion modeling for wildland fire planning

Increasingly, managers are utilizing smoke information in decisions involving wildland fire, ranging from planning prescribed burns, to helping evaluate options in incident response. How well can smoke information meet the needs of wildland fire managers? What are the most critical needs for advancing our ability to better model smoke dispersion? We examine the current state of smoke dispersion modeling, including what is being asked of the models and how well they are able to provide this information. The range of available smoke forecasts, smoke dispersion tools, and decision support systems are presented. Results from test cases are presented as well as feedback from those using current systems. The best successes and most critical failings of current smoke dispersion systems are evaluated from the context of both technical accuracy and the ability to support on the ground decisions.

4) Tim Brown*, Craig Clements, Sim Larkin – Results from the JFSP smoke model validation workshop

As part of the Joint Fire Science Smoke Science (JFSP) Plan, a workshop has been organized for late summer 2013 to address one of the plan's themes of smoke model validation. This workshop is purposed to develop a consensus approach to undertake smoke model validation through field measurements. It builds upon needs described in the JFSP Smoke Science Plan in the JFSP Models and Measurements Workshop, and lessons learned from the Rx Cadre field experiments. While smoke is a component of the Rx Cadre experiments, it is not sufficiently addressed to substantially advance smoke modeling and prediction, or to create an authoritative smoke measurement and modeling database. To do this, a select group of smoke, fuels and fire behavior scientists have been invited into a workshop forum to both formalize the research elements and strategies needed to advance smoke modeling, and to design and plan a field campaign that can significantly advance our understanding of smoke. This presentation will discuss the workshop, and plans for a field campaign aimed at improving smoke modeling and prediction.

5) Mark Finney* and Jack Cohen – Operation fire modeling and critical research questions

The rapidly expanding demand for operational fire modeling systems ranges from individual fire forecasts (single predictions) to continental scale risk analyses (ensemble simulations). The systems now employed are used in planning, operational support, and new research. All of these systems depend on having a common core set of fire behavior models that have simple computational demands, are robust to the unknowns and uncertainties of the fire and the environment, are responsive to the practical set of inputs available, and offer understanding of fire behavior to the user (not just another black box model). Although the limitations of the current core fire behavior models are well understood, the pathways to worthwhile replacements are not. Partly, this is because the requirements for fire models have never been identified. As argued here, however, the main reasons for no clear pathways to replacement are the absence of a confirmed theory of fire spread. In other words, we don't know how fires spread and modeling directions have created confusion rather than knowledge. Without such knowledge, the cost and rationale for replacing current models cannot be justified based on how adequately the physics of fire spread is represented (because it is not known and has been erroneously assumed). Recent laboratory experiments and field observations are presented that suggest an important new reason why the question of how fire spreads has remained unanswered. It suggests several critical measurements from field-scale burns that must be obtained.

6) Ruddy Mell* and Rod Linn – Future of coupled fire-atmospheric modeling

The spatial scales at which combustion and heat transfer occur in a wildland fire are significantly smaller than the spatial scales characterizing smoke rise and transport over a landscape. This scale separation makes it computationally expensive to simulate fire behavior and smoke transport with equal fidelity. As a result, operational models that focus on wildland fire behavior or smoke transport simplify, in different ways, the fire-atmosphere coupling. The coupling of the fire and atmosphere physics is relevant to a number of fire problem areas including fire fighter safety, fire effects, fire behavior in complex fuels and terrain, accelerating fire fronts, smoke generation, and smoke plume rise and transport. Thus, there is a need to improve the modeling of fire-atmosphere processes over a range of model applications. These improvements will come with a computational cost, which must be balanced against the increased model capability. This presentation will give an overview of potential advances in fire-atmosphere modeling given the increasing availability of affordable multiprocessor computing platforms. Also, advances in computer model capability need to be supported, when possible, by commensurate measurements. These measurements needs will also be discussed.

7) Craig Clements – State of fire-atmosphere interactions research for smoke and fire behavior modeling

Fire-atmosphere interactions are driven by the state of the fuels, ambient meteorology, and terrain. These interations often lead to complex circulations in and around the fire front that can impact its behavior and intensity and resulting smoke emissions and dispersion. While in the past decade, there has been a major research thrust in smoke emissions modeling and measuremens, there have been few studies aimed at better understanding fire-atmosphere interactions and their relation to smoke emissions. New observational remote-sensing technologies including scanning Doppler lidar and radar have been used to quantify the complex circulations in and around wildland fires. In addition to remote sensing, in situ eddy-covariance measurements have been used to quantify the turbulence characteristics of different fire regimes and investigate the validity of Monin–Obukhov simularity theory for use in smoke dispersion models. This presentation will present the current state of knowledge of fire-atmosphere interactions and future needs including measurement technologies and design of future field campaigns for disperison model development.

8) J. Kevin Hiers – Fire and smoke modeling to meet ecosystem management objectives

Managed fire regimes are now critical to meet all conservation objectives in fire-adapted ecosystems nationwide. Due to climate change, the introduction of non-native invasive species, altered fuel beds, the restoration and maintenance of these fire-dependent ecosystems and protected species contained therein faces nearly insurmountable uncertainty. The Department of Defense (DoD) is heavily invested in fire ecosystems of the desert southwest, southeastern US, and Alaska. In forest ecosystems, use of prescribed fire is an integral part of managed fire regimes, but the experience of managers, which is so important to risk management, will become less relevant given uncertainties. Trial and error approaches to management will not be a reasonable strategy to increasing uncertainty as smoke impacts and prescribed fire escapes are increasingly subject to litigation. In support of ecosystem management, modeling must become more mechanistic in it prediction and integrate prediction across multiple scales and ecological processes. No longer are empirical approaches satisfactory to meet the challenges of a no-analogue future. To meet the needs of future managers, process based models of ecological response to disturbance must be integrated with physics-based models of fire behavior to predict ecosystem feedbacks. Models of fire behavior and smoke management should more explicitly identify their domain of inference to managers. Related, models should clearly articulate unknowns and uncertainties for managers at both operational and planning timescales. Thresholds of ecological response to management must be identified in model predictions, and monitored for in the field through long-term.

9) Matthew Dickenson – Trends and major gaps in fire effects research and development

Advances in coupled fire-atmosphere modeling not only have important implications for fire behavior and smoke transport modeling, but also for predicting the effects of wildland fires. Fire effects of interest include the relatively direct effects of fires on soils, vegetation, and fauna. In turn, these direct effects influence longer-term, more contingent processes such as soil erosion, maintenance of diversity, fuel response, habitat change, and hydrological effects. Fires occur in fuels and environmental conditions that are often legacies of past disturbances including past fires, fuel treatments, hurricanes, mortality from insects and disease, and invasions by novel species and coupled fire atmosphere-models must be sufficiently flexible to respond to varying conditions created by these disturbances. Coupled fire-atmosphere models have only recently been used to understand fire effects, but the results are promising and new areas of application continually emerge. In this talk, we will illustrate the application of coupled fire-atmosphere models to fire effects prediction, including effects on trees and fauna. We will also explore new areas of application in which coupled models are likely to give results quite different from fire models currently in operation. Finally, challenges in using computationally intensive models for effects prediction will be discussed along with gaps in capabilities.