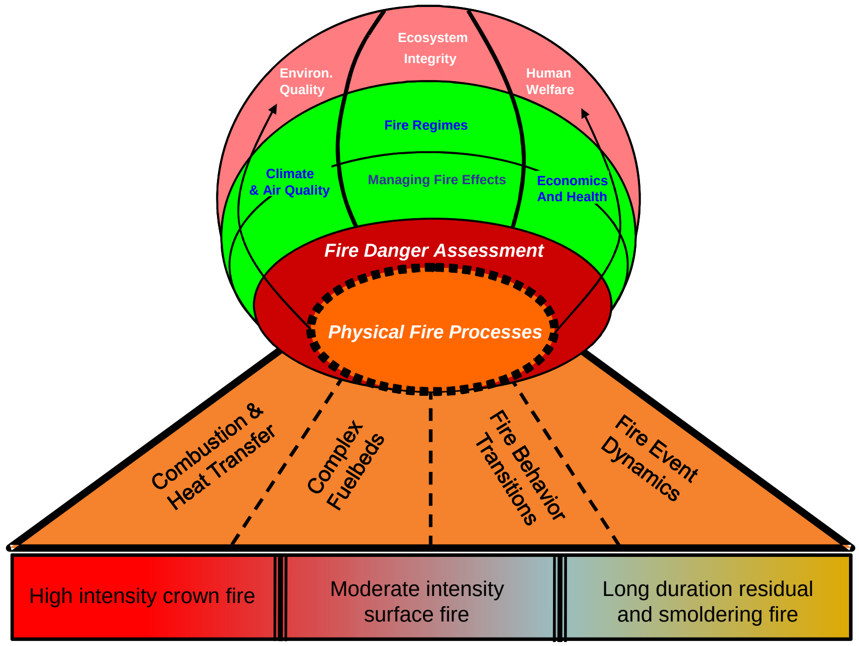
FIRE BEHAVIOR SCIENCE ADVANCEMENT PLAN

A PLAN FOR ADDRESSING PHYSICAL FIRE PROCESSES

WITHIN THE CORE FIRE SCIENCE PORTFOLIO



FINAL REPORT TO THE JOINT FIRE SCIENCE PROGRAM

BOARD OF GOVERNORS

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Contributors

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INTRODUCTION -- PURPOSE AND STRUCTURE OF THE PLAN

This document presents a problem analysis and science advancement plan for fundamental fire behavior research activities under the Physical Fire Processes Element (A1), Core Fire Science Portfolio (A), Fire Strategic Program Area (SPA), as defined by the Forest Service *Wildland Fire and Fuels Research and Development Strategic Plan: Meeting the Needs of the Present, Anticipating the needs of the Future* (fire and fuels R&D strategic plan*)*.[1] Development of the plan was solicited and sponsored by the Joint Fire Science Program (JFSP), project number JFSP-08-S-01, titled "Fire Science Advancement Plan."

The fire and fuels research and development (R&D) strategic plan on which this plan is based was recently reviewed by an external peer review panel. The review panel strongly recommended expansion of the Core Fire Science Portfolio commitment to comprehensive fire model development, while noting an apparent lack of internal coordination amongst the different Forest Service R&D parties. The review panel also notes: "the immediate present day challenge is to balance the efforts to develop a new, more flexible physics-based approach while at the same time providing a moderate level of support for the existing systems without resorting to a major overhaul to extend the life of their usefulness." Finally, the reviewers state, "it must be the highest priority within this [core fire science] portfolio."

This science advancement plan is a deliberate effort among leaders of Forest Service fire and fuels R&D to both mitigate the observed lack of coordination and expedite fundamental fire science research activities towards a new, comprehensive fire model. A national, grass-roots, boundary-less group of agency, academic, and fire scientists, called the Core Fire Science Caucus (the Caucus), initiated this dialogue in 2001, and many non-Forest Service participants in the Caucus have contributed to this Plan. The Core Fire Science Portfolio Management Team responsible for development of this plan owes considerable debt to the Caucus. Further, this Plan remains a living document and will continue to both inform and be informed by the Caucus.

The Core Fire Science Portfolio Management Team is proud to have successfully engaged 23 invited contributors from the fire science community in North America in a 2-day workshop and also in subsequent writing of this Plan and the associated study questions. These contributors (listed in Chapter III—Study Questions) represented three national laboratories or research centers, three universities, four Forest Service Research Stations, and the Canadian Forest Service. Additionally, the Plan has been reviewed and vetted by a cadre of external peer reviewers, assembled from the global fire community, whose comments contributed to this version of the plan.

This plan includes a recommendation for JFSP funding of three specific studies to begin in FY08, and also frames a broader set of science needs, study questions, and scientific hypotheses to be addressed in later years and/or with other funding. Our consideration is not

[1] The relationships of Physical Fire Processes Element (A1), Core Fire Science Portfolio (A), and the Fire Strategic Program Area (SPA), as described in the *Fire and Fuels R&D Strategic Plan*, are illustrated in fig. 1 on page 8.

limited to Forest Service Research; rather, it involves the broader fire science community in both its development and its expected implementation. The three studies submitted under this Plan include strong partnerships and collaborations among many partners—each study plan explicitly lists Team members and contributors.

We present this plan in four chapters and an appendix:

I. **Summary of the Core Fire Science Framework:** The framework was first developed by the Caucus, then later revised and adapted for inclusion in the fire and fuels research and development (R&D) strategic plan. We include the framework in its entirety, providing context and to introduce the areas of investigation in four science elements.

II. **Problem Analyses for Physical Fire Processes**: The Team and the workshop participants developed these to provide a perspective from each of four elements in the framework.

    A. Combustion and Heat Transfer

    B. Complex Fuelbeds

    C. Fire Behavior Transitions

    D. Fire Event Dynamics and Fire-Atmosphere Interactions

III. **Study Questions:** These 17 "straw prospectus" documents comprise a series of achievable study questions that would test physical science hypotheses that are critical to both the fundamental and incremental improvement in fire management decision support systems, disposition of questions, and a list of scientists who collaborated to write the study questions.

IV. **Immediate (FY08) Core Fire Science Portfolio Team Funding Priorities and Draft Study Plans:** Questions selected by the Core Fire Science Portfolio Team for immediate investment by the Joint Fire Science Program (3 studies) and National Fire Plan (2 studies). We first align and summarize each of the study questions within the context of their four respective Problem Areas. We then discuss our criteria for filtering these into three suggested study plans, and the reasons for disposition of each of the original 17 study questions.

Appendix: Responses to reviews of this advancement plan by national and international peers. We provide responses both to general comments and to specific comments provided within the text, and provide reconciliation for each/all comments.

This plan is not the end of the story, just another step in a continuing collaborative process. Our goal is to achieve a national boundary-less community of fire scientists to identify and solve the most critical fire science questions. In these past six months, we have assessed the problem, broadly and identified a few specific studies that deserve immediate support, but have not yet advanced a complete life-cycle assessment of the sequencing and interactions among the full scope of studies needed to provide a comprehensive solution. That development is ongoing, with a more complete ranking of priorities expected in another half year.

This is also an exercise by the portfolio management team to coordinate the U.S. Forest Service Research component of core fire science, to foster integration with the larger national and international science communities, and to advise others of our sense of priorities for Core Fire Science, Physical Fire Processes. This is a trial management process wherein the portfolio management team and the Board of Governors of the Joint Fire Science Program share the responsibility for identifying the most productive research directions and the most promising research proposals for funding within the scope of Physical Fire Processes research. We look forward in the future to exploring this and other types of partnerships with the Board and other funding institutions.

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I. SUMMARY OF THE CORE FIRE SCIENCE FRAMEWORK

This fire behavior science advancement plan evolved from the "Core Fire Science Framework (05/17/06)" developed by the core fire science portfolio team. That document defined the core fire science portfolio in relation to other portfolios and strategic program areas (SPAs); it developed a 15-year vision for each of the three elements within the portfolio; it presented a preliminary prioritization of immediate activities and outcomes, and it provided an introduction of the concept of a virtual national fire science laboratory encompassing Forest Service fire labs, other national labs, and universities.

In this chapter we summarize the research and development questions (or problems) identified by the core fire science cross-station team as relevant and critical to three elements within the core fire science portfolio: A1—physical fire processes, A2—fire characteristics at multiple scales, A3—fire danger assessment (fig.1).

IMPERATIVE

Fire has important positive and/or negative effects on a wide range of human values. New, invigorated core fire science research will provide the underpinnings for incorporating an improved understanding of fire behavior, combustion, fire weather, emissions and other key processes into tools to improve the efficiency and effectiveness of fire and fuels management decisions. This research will lead to enhancements in public safety, ecosystem integrity and sustainability, and environmental quality. The Core Fire Science domain is illustrated in fig. 2, where the relationships and scale hierarchies of the three portfolio activities (italics) are shown with respect to the five portfolios. Managing these effects is a central mission of fire and resource management. Reliable and accurate assessment of fire hazard and risk, fire effects, and fire ecology at multiple scales are essential, and no assessment can be more accurate than the core fundamental understanding of Physical Fire Processes.

The development and implementation of core fire sciences and core fire behavior modeling has not kept pace with changes in management needs and the demands of evolving policies. We have continued to rely largely on science and applications developed in the 1950s-to-1970s period. While sound and valid, the science developed in the 1970s was highly constrained by the technologies available for its implementation and its focus on moderate-intensity flame spread in surface fuels. The fire management community, complacent with past successful fire research and development, has overextended the scientific relevance of core fire knowledge.

Current operational fire behavior models do not accurately reflect the complexity of combustion processes, the temporally and spatially variable physical environment in which they occur, or fire-atmosphere interactions. As a result, predictions are often inaccurate in ways that negatively affect fire planning and response. Improved basic understanding of physical and chemical fire processes and interactions is a critical need for development of the next generation of decision support and predictive tools for fire and fuels management. Equally critical is the need to integrate this understanding into accurate spatial and temporal predictions of fire processes and tie to environmental effects (e.g. use fire outputs and inputs into "effects" predictors."

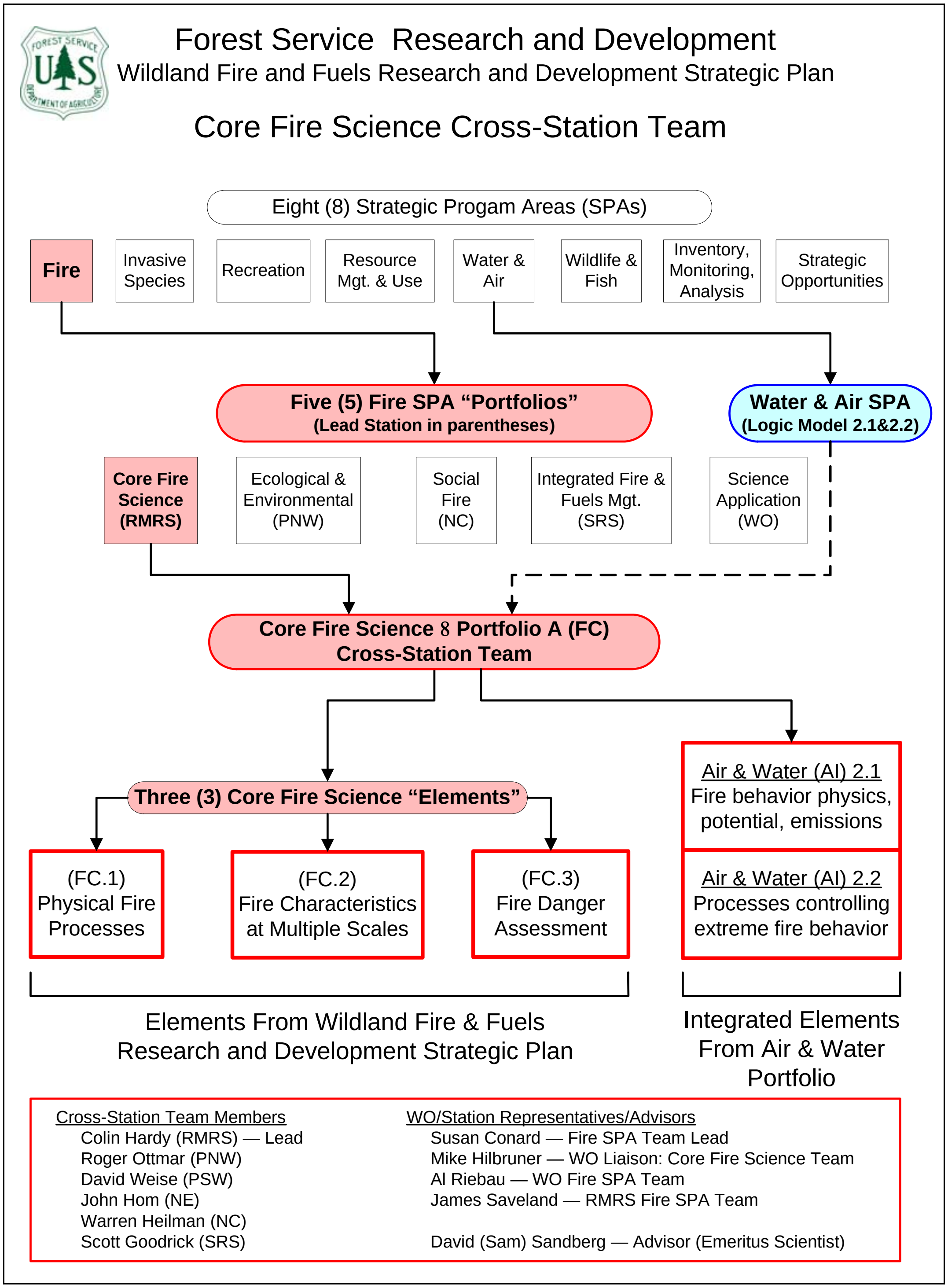

Fig.1—Schematic showing the three core fire science elements (labeled here as FC.1, FC.2, and FC.3 for elements A1, A2, and A3, respectively) as they relate to the core fire science portfolio within the fire strategic program area (SPA).

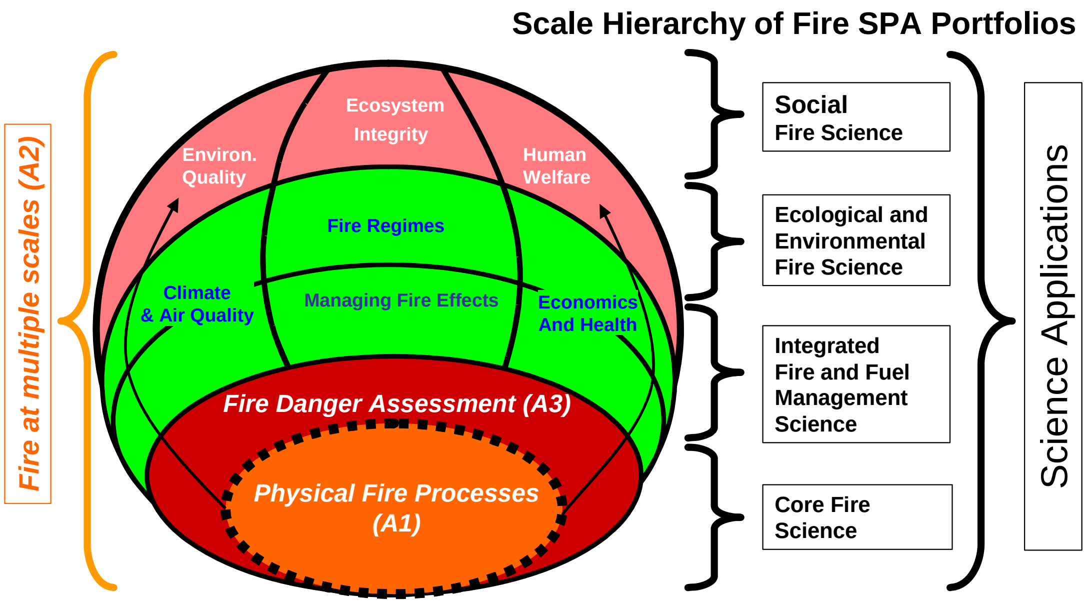

Fig. 2— The Core Fire Science "onion" illustrates the relationships and scale hierarchies of the three portfolio elements/activities (A1, A2, and A3) with respect to the five fire SPA portfolios (labeled on the right-hand side--see fig. 1 for context).

A Virtual National Fire Sciences Laboratory

Within Forest Service Research, core fire science expertise is located among all research stations and at the Forest Products Laboratory. These labs, with their scarce resources, often work on related topics. Many efforts have the unfulfilled potential for collaboration, and some are either inefficient or redundant. Frequently, these efforts share a national mission or scope, but are unnecessarily constrained by local or Station-centric authorities. Contributors to Core Fire Science Portfolio RD&A activities are evolving toward a National Fire Sciences Laboratory to work on priority core fire science problems. This "virtual laboratory" is self-organized, placeless, and is principally accountable to the fire SPA team. Stations would make scientist time as well as core fire science facilities and resources available for the priority tasks and would receive funding through the appropriation process for this work. Additional, highly-capable core fire science expertise exists throughout the federal government outside of Forest Service. To answer questions of national significance—most core fire science questions have no geographic or ecological boundaries—the model for a National Fire Sciences Laboratory necessarily includes the establishment and nurturing of partnerships with national laboratories as well as universities.

Defining the Core Fire Science Portfolio

Scientific investigation of physical fire processes is at the core of fire research. It advances the fundamental understanding of fire-fuel-atmosphere interactions, fire behavior, fire danger, and fire emissions in all fuels and fuel complexes. This understanding is critical for developing timely, accurate, and complete predictions of fire behavior and effects; improving assessments of fire hazards and risks; designing and comparing fuel treatments and outcomes; and prioritizing fuel treatment and response options.

Physical Fire Processes (Element A1)

Improve our understanding of the fundamental, multi-scale, physical processes that govern fire behavior, including combustion processes, heat and energy transfer processes, and fuel-fire- transitions from "well behaved" to extreme atmosphere interactions and dynamics in complex fuelbeds and environments. [*Informed by A3 activities]*.

The outcome of this research will be a comprehensive physics-based fire modeling system in that it includes the full range of combustion environments, and fire events relevant to the needs of fire managers. We define a combustion environment as the combination of fuel involvement, heat transfer mechanisms, and scales that are present at any contiguous element of time and space. An event is the set of combustion environments that constitute a wildland fire or prescribed fire from the time of ignition to the cessation of the last smoldering ember. This element provides the fire-physics input to fire management decision support needs that include planning, operations, monitoring, and assessment.

The physical fire processes element was further classified (in the core fire science framework) into five sub-elements: (1) combustion and heat transfer, (2) complex fuelbeds, (3) fire behavior transitions, (4) fire event dynamics, and (5) emissions. Among the five sub-elements, we have excluded fire emissions from consideration for priority status and from the following problem analysis. While important questions still remain such as predicting the formation of noncriteria pollutants, particulate morphology, secondary pollutant precursor formation, and plume behavior, none of these problems can be solved without first solving some of the problems remaining in the 4 first sub-elements. Furthermore, published problem analyses are already available (Sandberg et al. 2001, 2002) so anything we would add now would be redundant to those efforts.

The four sub-elements selected for consideration in this science advancement plan are illustrated in the context of the "core fire science onion" in figure 3. These four sub-elements of physical fire processes—combustion and heat transfer, complex fuels, fire behavior transitions, fire event dynamics—were identified as avenues of research that would lead to improved decision support for fire management.

Combustion and Heat Transfer

- Improve our ability to model and predict the level of heat transfer to and heat absorption by ground fuels, vegetation, the atmosphere, and the soil during all phases of combustion under varying fuel conditions.
- We define a combustion environment as the combination of fuel involvement, heat transfer mechanisms, and scales that are present at any contiguous element of time and space.

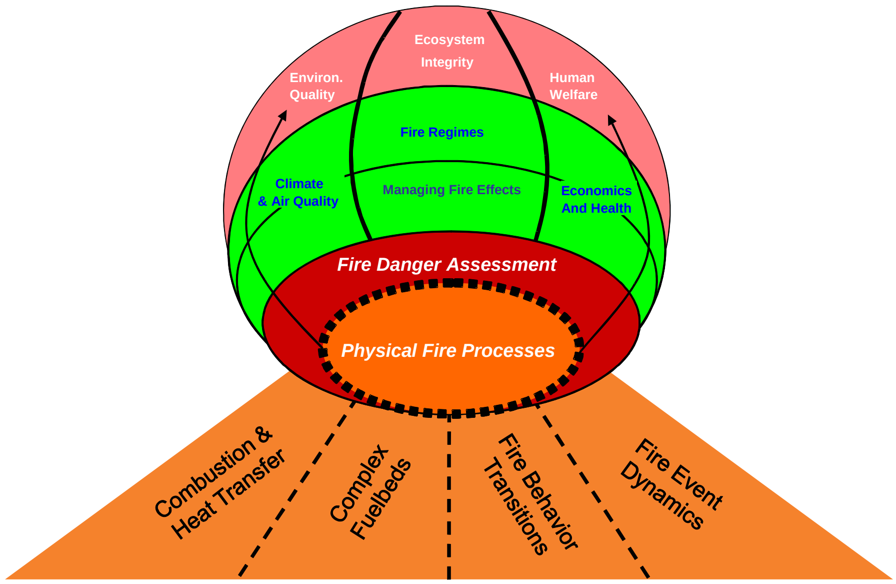

Fig. 3—Four selected sub-elements of physical fire processes in the context of the "core fire science onion."

- Understand, measure, and model the thermophysics and chemistry of each important combustion environment, including the thresholds of fuel involvement, mechanisms and scale of heat transfer, combustion processes, fuel consumption, and residence time. We will expand our knowledge beyond moderate intensity steady state surface fires to the physics of the full range of environments from the single smoldering fuel element to the large-scale mechanisms of heat and mass transfer that typify mass conflagrations.
    i. Consumption of fuel during all combustion phases that provide heat for adjacent particle pyrolysis.
    ii. Residence time for all phases of combustion; time/temperature history of combustion.
    iii. Fuel particle ignition threshold.
    iv. Better describe the roles and importance of heat transfer by convection, radiation, and conduction as related to fire spread, energy transfer to receptors, and transitions in fire behavior.
    v. Describe the roles and importance of heat transfer by mass transfer of firebrands.
    vi. Energy transfer from surface to aerial fuel.

Complex Fuelbeds

Characterize complex fuelbeds and determine their impacts on fire characteristics, including the impacts of different horizontal and vertical vegetation fuel structures, different live and dead fuel compositions, and complex fuelbeds composed of vegetation and buildings.

i. Characterizing spatial and qualitative complexity of fuelbeds.

ii. Interaction between fuelbed components within a combustion environment—vertical strata.

iii. Interaction between fuelbed components within a combustion environment—horizontal strata.

iv. More complete description of combustion that includes the differences between dead and living fuels

v. Distinguishing combustion characteristics of rotten fuels and organic layers.

vi. Dwellings and structures as a fuelbed component in wildland fire.

Fire Behavior Transitions

- Determine the physical processes responsible for major transitions in fire behavior; including surface spread initiation, fire extinction, crowning initiation, fire cessation, and structure ignition.
- Transition from moderate intensity flames in surface fuels to very high intensity fires that involve tree canopies and/or long-range (i.e. >10m) heat transfer.
- Anticipate transitions between fundamentally different combustion environments such as:

    i. Transitions from fires involving interactions among fuel components to independent combustion of individual fuel component(s).

    ii. Transitions from ignition to propagation (and from spread to no-spread) for all combustion environments.

    iii. Structure ignition from fire in wildland fuel.

    iv. Transition of fire propagation from surface to crown (passive crown fire), and from individual to multiple crowns (active crown fires).

    v. Transitions from flaming to smoldering to residual smoldering combustion.

    vi. Transitions that involve convective feedback from collapsing plumes.

Fire Event Dynamics

The spatial and temporal pattern of fire physics that constitute an event. An event is the set of combustion environments that constitute a wildland fire or prescribed fire from the time of ignition to the cessation of the last smoldering ember.

i. Spatial interactions of multiple combustion zones.

ii. Spatial and temporal variability of multiple combustion environments within and event.

iii. Characteristics, thresholds, and dynamics of blowup and plume-dominated fires.

iv. Interactions of ambient atmospheric structure/turbulence field and fire-induced turbulence structure and buoyancy.

Fire Emissions

- Improve our understanding of the physical and chemical processes producing response; like emissions, including pollutant formation, primary combustion product formation, and plume (convection column) characteristics and behavior.
- Enable a comprehensive, physics-based system for prediction of event-scale heat release rates and emissions source strength for all types and phases of wildland fire; and for expressing the primary plume dynamics from which plume rise models could be developed.
    i. Heat release, plume buoyancy, and primary plume dynamics.
    ii. Emissions from residual smoldering combustion.
    iii. Organic-to- elemental carbon ratios in PM emissions.
    iv. Trace gas and secondary pollutant precursor emissions.

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II. PROBLEM ANALYSES FOR PHYSICAL FIRE PROCESSES

COMBUSTION AND HEAT TRANSFER

Problem Description

Fire management decision support in the modern era requires predicting ecological, environmental, and social impacts of fire use and fire control and an improved anticipation of transitions to extreme fire behavior that threaten human safety and property. Physical fire science is at the core of fire research. We cannot significantly advance our ability to support fire management without expanding our knowledge of combustion and heat transfer and incorporating that knowledge into the capability to predict the initiation, rate, intensity, and duration of all stages of combustion, and to better quantify the mechanisms and efficiency of heat transfer under a wide range of fuel characteristics and environmental conditions.

Fire behavior is not a one-dimensional and steady state process (as currently modeled) but is the result of combustion of numerous live and dead fuelbed elements arranged non-uniformly on a landscape. We must improve our modeling framework and underlying basic knowledge to reflect the complexity of combustion limits, vectors of heat transfer within the fuelbed and across gaps in fuels, the role of live and dead fuel moisture in damping combustion, and the residence time of combustion in all stages.

Justification

Wildland fire management objectives during the first 80 years of the last century focused primarily suppression of surface fires. Decision support systems focused on predicting the rate of spread and intensity of free-spreading flames in simple (homogeneous), continuous (uniform) fine surface fuels, so that initial attack and fireline construction tactics could be tailored to current and predicted fuel moisture and wind speed conditions. From this starting point, fire managers have been expected to utilize expert judgment in accounting for complex fuelbeds; transitions to extreme fire behavior or to other stages of combustion; or event-scale fire-atmosphere interactions or the interactions of multiple combustion environments.

For a variety of reasons, fire management objectives now encompass a much broader scope requiring capabilities not possible with the current fire modeling tools. To improve firefighter safety, improvement is needed in the ability to anticipate transition of well-behaved surface fires to extreme events that involve aerial fuels and large-scale turbulent heat transfer Event (or)-scale strategies for containment or use of fires depend on predictive spatial tools that recognize natural and managed fuelbed non-uniformity, the interaction of multiple heat sources, complex fire-topography-atmosphere interactions, and diurnal variation and long term changes in the fire environment. Managing fire in the WUI requires more precise understanding of combustion and heat transfer in environments that include structures, landscaping, and highly modified natural fuelbeds. Managing fire severity and fire effects (vegetation mortality, smoke production, carbon transfer, soil heating, etc) depend on modeling the initiation, consumption, rate, and residence time of all stages of combustion (including residual smoldering) in organic soil layers, live fuels, and coarse fuel elements.

Current State of Knowledge and Inadequacy

Current U.S. operational systems for fire behavior (BEHAVE [Andrews and Bevins 2003; Andrews et al. 2005], FARSITE [Finney 1995; Finney 2004], FlamMap [Finney 2006], FSPro [USDA Forest Service 2007], etc.) and fire danger (NFDRS [Deeming et al. 1977; Burgan 1988]) use the same fire spread, intensity and flame length models—the Rothermel fire spread model (Rothermel 1972; Andrews and Rothermel 1982; Rothermel 1993) accompanied by Byram's flame length fireline intensity (Byram 1959) correlation. The basic one-dimensional structure of this model is applicable to the relatively simple case of a moderately intense steady-state flaming front in simple, uniform fuelbeds, but new approaches must be taken to address transitions in fire behavior (Cohen et al. 2006a; Cruz et al. 2006a; Cruz et al. 2006b), fires in complex fuelbeds (Sandberg et al. 2007a), fire-atmosphere interactions, and fire effects. Other problem analyses expand on each of these topics and identify new research and development needs. This problem analysis addresses fundamental new approaches to the understanding and modeling of complex fire behavior and explores incremental improvements to current decision support systems based on solving new physical science questions about combustion and heat transfer within the combustion zone (i.e. a contiguous four-dimensional space wherein mass and energy interact)

Approach to Problem Solution

Future prediction capabilities will rely on establishing greater understanding of wildland fire dynamics. This will necessarily involve research on the combustion of live and dead fuels; flame zone radiation and convection heat transfer; fuel pre-heating and decomposition, combustion rates and residence times; and the minimum requirements for flaming, smoldering, and residual combustion. Specific research issues have been identified that offer potential for significant advance:

Flame Structure and Variability

Experiments and modeling have shown that convective heating from flame contact is in some cases essential for fire spread within a continuous fuelbed and that the vertical structure and non-steadiness of flame flow (from turbulence) is key to describing flame bathing of fuels near the leading edge of an heading fire (Cohen et al. 2006a; Cohen et al. 2006b). Yet flame dynamics are some of the least understood characteristics of fire behavior (Yedinak et al. 2006; Anderson et al. 2006) and must be described to overcome modeling challenges associated with fuel discontinuity and spread thresholds.

Combustion Limits of Live and Dead Fuels

Ignition and burning thresholds of live fuels are observed to require a minimum "clump" or density of particles for a particular heating rate. Similar thresholds in dead fuels may depend on the lean combustion limit. An emphasis on combustion limits of fuel clusters is required for a physical definition of continuity and sustainability within portions of a fuel complex including both live (Jolly 2007) and dead vegetation. Recent work also suggests that the model for the heating of a fuel particle to ignition which has been the basis for current fire behavior models may also be incorrect. The mass transfer of moisture within a fuel particle in response to heating is another key factor in determining combustion limits. In summary, the relationships between the energy imposed on a clump of fuel particles and the resulting energy and mass transfer need to be more explicitly measured and modeled.

Radiant/Convective Energy Partitioning

Radiation sources in wildland fires have long been suspected to depend heavily on the solid fuels burning within the fuelbed because flames are thermally thin. From sources within the fuelbed itself, radiation heating of particles is likely to be effective at "short" distances from the advancing fire edge because (1) radiation penetration within fuelbeds is limited by optical interference among the particles, and (2) radiation heating is offset by convective cooling. This illustrates the need to quantify energy budgets within fuelbeds in terms of radiant and convective sources within and external to the fuelbed (Cohen et al. 2006a) and in terms of particle temperature/moisture dynamics.

Rates and Residence Times

Prediction of non-steady state fire behavior which incorporates transitions, and complex fuelbeds, and prediction of fire effects all require treatment of the rate of combustion and residence times in a mixture of fuel elements. Residence time is a function of fuel element size, condition, and overall combustion efficiency.

Live Fuel Moisture Influence on Combustion

There is little evidence available to improve on the current modeling assumption that live fuels influence combustion as if they were simply very wet dry fuels (Fosberg and Schroeder 1973). This over-simplifying assumption neglects that there are several classes of live fuels and that they include a range of moisture from free to physiologically-bound to solution moisture in live woody, broadleaf foliage, and coniferous foliage fuelbed categories. Current decision support models so not incorporate empirical advances suggested by Wilson (1990) or Catchpole and others (1998); let alone incorporate the fundamental differences in the several classes and sources of live fuel moisture damping.

Long-term Improvements

Future improvements in understanding and managing wildland fire require improved tools for simulating fire ignition/extinction, transition, and intensity. This is only possible through a renewed and focused research approach leading to incremental improvements in knowledge and subsequent applications to new applications based on fundamental departure in theory and approach.

Incremental Improvements

Some of the limitations of current fire behavior models can be resolved by expanding the dimensional formulation of the models (e.g. Sandberg et al. 2007a; Sandberg et al. 2007b) to reflect an improved understanding of:

- Heat transfer discrimination (propagating flux) by internal (to the fuelbed matrix) and free (by wind) convection, and radiative transfer between fuel elements.
- Combustion efficiency as affected by air:fuel ratios, oxygen diffusivity, fuel characteristics, and environmental conditions
- Live fuel effects on combustion efficiency and fire propagation
- Moisture effects on combustion efficiency and fire propagation
- Energy balance at the initiation and extinction of spread and flaming stage.

- Formulation of new model approaches for heterogeneous and spatially non-uniform fuelbeds.

Addressing these immediate needs will also be necessary in the long term for replacing current fire behavior models with new technology.

Fundamental Departures in Theory and Approach

The next generation fire model will likely result from the application of new theory and a marriage of analytical and numerical solutions. Many complex processes of combustion, heat transfer, and fluid dynamics will never be observed experimentally. We will test hypotheses and perform more experiments through numerical simulation. Yet we may never reach the point where real-time fire behavior prediction is accomplished through dynamic simulation, but will always require some analytical approximations calibrated in laboratory environments. Future fire models must include:

- Solutions for the residence time of all stages combustion in all fuel categories and conditions
- Advanced treatment of turbulent convective energy transfer at all scales from the centimeter to tens-of-meter scales
- Separation of heat transfer mechanisms within the fuelbed matrix, above the fuelbed, across gaps within the fuelbed, and among dissimilar components of the fuelbed.
- Time sequenced combustion and heat balance modeling, simulating the energy production and sink at all stages of fuel condition (e.g. moisture content, temperature, size, chemistry, porosity, diffusivity) at all stages of combustion (pre-heating, ignition, flaming, smoldering, residual combustion)
- Discrete solution of small-scale heat transfer such as in backing fires, litter fires, grass
- Analytical modeling of fire spread through ignition point transfer such as when burning litter, grass, or bark transported by wind controls rate of spread and energy transfer.

What will we Accomplish First, and How?

Refer to individual questions submitted in Section VI.

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COMPLEX FUELBEDS

Problem Description

The physical characteristics (e.g., fuel loading (mass per unit area), depth, height, structure, arrangement, continuity, density, bulk density (mass of dry fuel per unit volume), species, material type) of live and dead biomass, and building materials along with the internal moisture condition contributes to the character, size, intensity, duration, and heat output of surface, crown and structural fire. Since fuels are often complex and diverse, quantifying these characteristics and conditions spatially across the landscape will be extremely critical in the understanding and predicting the ignition potential, heat transfer, fire behavior, and heat output as we move into the next generation of fire models.

This problem analysis will describe where we are and where we need to go in order to characterize complex fuelbeds and determine their impacts on fire characteristics, including (1) live and dead moisture content; (2) spatial and qualitative fuel complexity; (3) horizontal and vertical vegetation fuel structures; (4) rotten fuels and organic layer characteristics, and (5) buildings as fuelbed components. The fire transitions, combustion and heat transfer, and fire event dynamics problem analysis within this plan depends upon and expands on each of these topics and identifies new research and development needs.

Justification

Physical and semi-empirical models for large- and small scale fire assessments (FireTec, BEHAVE, FARSITE, FlamMap, FSPro, FCCS, SIAM, WFDS, etc.) are becoming more complex, requiring a comprehensive characterization of fuelbed structure, moisture content, depth, height, density, arrangement, continuity, bulk density, and species mixtures by fuelbed category that captures the structural complexity and spatial non-uniformity found across landscapes. Dwellings and structures are also considered a fuelbed component requiring information on material and design for strict code. Only then will we be able to improve our predictive capability of three critical sub-elements defined in the core fire science framework including fire transitions, combustion and heat transfer, and fire event dynamics.

All real-world fires involve complex fuelbeds made up of mixtures of fuelbed components and live and dead moisture content arranged in heterogeneous, non-uniform, and discontinuous patterns. Although various procedures have been developed over the past 35 years to characterize fuelbeds for fire behavior and fire effects model inputs, they often included only the portion of the fuelbed components required by the application they were designed to support or were limited to homogenous bulk fuelbed properties. No physical-based consideration of energy production, transfer, or absorption in heterogeneous, spatially non-uniform, or discontinuous fuelbeds is possible without new theoretical and experimental approaches. Consequently, fuelbed descriptions, characteristics, structural complexities, and geographical diversity required by the next generation of fire models are not accounted for.

Fires are seldom a steady-state process, but are influenced heavily by the variability and discontinuity within fuelbeds. Vertical and horizontal discontinuities in fuelbeds most often limit whether a fire spreads and which aerial fuel categories become involved in combustion.

Fire behavior within a single combustion envelope is most often the expression of energy interactions between fuelbed categories and strata (in relation to physical structure, abundance, and moisture condition) fuel elements.

In addition to the fuel characteristics is the fuel condition or fuel moisture. Techniques for rapidly measuring moisture content in both live and dead fuels and new approaches for modeling and remote sensing fuel moisture are currently inadequate. This information is critical for improving our ability to account for moisture in live fuels and porous fuels and how it limits combustion. Complex fuelbeds that are a mixture of several live and dead components compounds this issue.

Current State of Knowledge and Inadequacy

Beginning in the mid 1930s, wildland fuels were classified by rate of spread and resistance to control (Hornsby 1936). Fahnestock (1970) introduced a set of dichotomous keys that rated spread rate and crowning potential of fuelbeds utilizing fuelbeds characteristics. Fahnestock's system was evaluated in several different fuel types across the country. Attempts have been made during the past 35 years to develop systems to construct and classify fuelbeds for loading and other characteristics with various degrees of success. These include the original and expanded fire behavior fuel models (Albini 1976; Scott and Burgan, 2005), National Fire Danger Rating System fuel models (Deeming et al. 1977), Fuel Condition Class System fuelbeds (Schaaf 1996; Ottmar et al. 1998), First Order Fire Effects Model fuelbeds (Reinhardt et al. 1997; Reinhardt and Crookston 2003); Canadian Fire Danger Rating System (Hirsch 1996); Australian Fire Danger Rating System fuel models (Cheney and Sullivan 1997; Cheney et al. 1990); Photo Series (Ottmar et al. 2007), the Fuel Load Models (Keane 2005; Rollins 2006; Lutes et al. in preparation), and the Prometheus system (Prometheus 1999). Many of these models were designed for specific software applications or as inputs to predict specific fire behavior and effects and often were restricted to outputs of fuel loading for general fuelbed categories. These systems did not capture the characteristics for all fuelbed categories, sub-categories, relative cover, and transitions zones between fuelbed strata and categories that are required to estimate heat transfer and the resulting fire behavior, fire event dynamics and fire effects (Ottmar et al. 2007, Riccardi et al. 2007).

We have acknowledged the importance of other fuelbed characteristics that will need to be quantified. In anticipation of this need, the Fuel Characteristic Classification System (Ottmar et al. 2007) was developed to capture the complexity and diversity of wildland fuelbeds in the United States by accounting for all fuel particles available to burn. However, there are several fuelbed attributes that are not accounted for or need modification, including (1) spatial variability, (2) improved accountability for live and dead moisture content, (3) improved definition and calibration of fuelbed depth, (4) improved description of specific fuelbed subcategories such as perched litter, basal accumulation, and dwelling and structure materials, and (5) improved characterization of transition between fuelbed strata and categories such as tree over story, mid-story, and understory, grass and shrubs, and litter and small woody fuels.

We have also realized the importance of moisture content within the fuelbed components. Direct measurement of fuel moisture through oven drying samples has been determined to be the most accurate method for estimating fuel moisture content. Although various electronic sensors on the market are available, they are unreliable for live fuels, fuels that contain rot, and fuels that have moisture contents higher than 30 percent. Fuel moisture modeling based on weather inputs has been limited to sound woody fuels (Fosberg et al. 1981, Simard 1968, Nelson 2001) and are not reliable or in existence for live fuelbed components or porous fuelbed components such as rotten logs and duff. Algorithms have been completed and implemented for detecting a greenness index through satellite imagery; however, this is for representing the general trends of live fuels at a very large scale.

Fire behavior models, including analytical solutions such as those based on Rothermel as well as numerical solutions such FireTec and WFDS assume fuelbeds as porous arrays that are homogeneous for at least one cubic meter, even though the heat transfer processes and the fuelbed structures that control or limit fire behavior may be much smaller in scale. Ignition thresholds and energy requirements of individual fuelbed components (especially live fuels) must be better understood to enable a physic based approach to fire behavior in heterogeneous fuelbeds with a mixture of live and dead moisture conditions.

Approach to Problem Solution

As we approach a new era in fire behavior modeling, a more precise accounting for complex fuelbeds will be required. Efforts to develop new or modify existing procedures and systems to account for complex fuelbeds and distribute and display those characteristics spatially across the landscape will have to be initiated. These procedures and systems will have to account for live and dead moisture content, vertical and horizontal continuity, differences between organic layers, and describe dwelling and structure materials. Although research and product outputs from the physical fire processes sub-element activities may eliminate or add fuelbed characteristics or conditions to a future research agenda, the current critical new knowledge ranked by priority expressed by the core fire team includes the following:

1. More complete description of moisture content and the effects of fuel moisture in limiting ignition and damping combustion efficiency are essential for understanding and modeling fires that include dead and living fuels.

2. Characterizing the spatial and qualitative complexity of fuelbeds concentrating on the transition and energy exchange between fuelbed strata, categories, and subcategories

3. Interaction between fuelbed components within a combustion environment—horizontal variability and discontinuities and vertical strata and the energy flow in the gaps between strata

4. Distinguishing combustion characteristics and combustion limits of rotten fuels and organic layers in all stages of combustion

5. Dwellings and structures as a fuelbed component in wildland fire.

Future improvements to the understanding of fire behavior and the combustion process will be accomplished only if there is a committed and focused research approach to describing complex fuelbeds. The suggested approach for each of the 6 specific research issues identified for significant advance are as follows:

More complete description of moisture content or condition of fuelbed components.

Experiments have shown that moisture content is an important fuelbed condition that drives combustion. However, moisture content is extremely variable and current techniques to determine moisture content need to be improved. The scale of measurement of fuel moisture is important. Direct fuel moisture measurements by collecting samples work well but many samples need to be colleted and values cannot be calculated for 24 hours. Moisture probes need calibration specific to species and are inaccurate at the higher moisture content values. Moisture surrogates such as fuel sticks only work for smaller fuels and do not consider changes that may occur in deep fuelbeds. Finally, moisture modeling has been attempted but is totally inadequate, especially for the duff, live moisture and rotten woody fuel moisture contents. The University of British Columbia has developed a watershed scale soil moisture model that could be evaluated for use in determining duff moisture content. There has been some success correlating moisture content measured on the ground with remotely-sensed water content of vegetation using a variety of satellite and aircraft-based sensors although frequency of imageries and cost may be of a concern. These approaches have ranged from simple measures of greenness of vegetation to sophisticated measures of water content based on spectral reflectance in certain narrow wavelengths.

Improved moisture modeling and sampling techniques must be described to better estimate moisture conditions of each fuelbed component.

For dead and rotten fuel moisture contents, investigations into moisture probes or a sophisticated modeling approach using physical process involved in moisture diffusion could be undertaken. For live moisture content, fuel moisture sampling protocols, moisture probes or new modeling techniques could be investigated. Further inquiry into the use of remote sensing should also be considered for both live and dead fuel moisture content estimation. This work will require 5 years and include an engineer and staff at the Riverside Fire Lab or Missoula Fire Lab in cooperation with the Technology Development Centers.

Characterizing spatial and qualitative complexity of fuels.

The characterization of the each fuelbed component and spatially applying those attributes is important to improving our ability to understand and predict the physical fire processes of fire transitions, combustion, emissions, and fire event dynamics. During the last 5 years, fuelbed characterization and applying this through GIS has advanced through the development of the FCCS (Ottmar et al. 2007) and LANDFIRE (2007) in anticipation of this need. Yet, there are several key fuelbed attributes that could be added to and refined in the current systems such as testing the flammability of species, improved abiometric equations for trees, shrubs, and grasses, improved bulk density conversions for deep organic layers, and most important, improved and accepted protocol for measuring fuelbed depth, fuel loading, and other characteristics. In addition, aerial and ground based lidar technology is advancing at an extremely fast pace with costs of imagery dropping and will possibly provide improved fuelbed characterization parameters forgoing the need to on the ground measurement of certain fuelbed components. Both the United States and Canada are leaders in this technology. Finally, aerial and remote sensing techniques need to be refined and improved upon so that specific change agents and other specifications can be attributed for spatial application of fuelbed characterization.

Improved biometric equations and bulk densities for several fuelbed components and flammability thresholds for important live species are needed. The continued modification and improvement of the FCCS is desirable. This would be a 5-year effort with involvement of the Pacific Wildfire Sciences Laboratory (PWFSL), Rocky Mountain Fire Sciences Laboratory (RMFSL), Pacific Southwest Fire Science Laboratory (PSWFSL), and National Institute for Standards and Technology (NIST). The spatial application, aerial detection, and LIDAR research would be initiated by the PWFSL, RMFSL, PSWFSL, and the Northern Research Station (NRS). The Southern Station is notably absent from this activity. There are resources in the South that are working on this problem and could continue to work on the problem.

Vertical and horizontal description of the fuelbed.

Gap analysis and fuelbed components that crossover those gaps both in the horizontal and vertical dimension are the key ingredients to describing the surface and crown fire spread and transitioning to crowns. Previous research has characterized fuelbeds strictly by general fuelbed groups such as trees, shrubs, grasses, downed woody fuels, litter, and duff and never considered size of gaps or fuelbed categories or subcategories that carry the fire both vertically and horizontally (e.g. limbs, bark, vines, lichen, moss, tall shrubs and grasses and needle drape).

Improved characterization of the gaps and fuelbed components that enable fire to transition from one fuelbed strata to another is needed. The FCCS has begun the process to capture the gap analysis but major improvement could be made. New standard protocols need to be developed on how to quantify ladder fuels and gaps, and determine the specific fuelbed characteristics that will sustain flames to vertically or horizontally carry across gaps between fuelbed strata or categories. As indicated above, lidar has great potential to assist in the description of the horizontal and vertical components of fuelbeds. As part of an NSF-funded university consortium effort, several vegetation types throughout the country have been measured using LIDAR (Light Detection and Range). This dataset could provide a great deal of information that could be extrapolated to similarly structured fuelbeds. This effort will require 2 scientists 5 years and should be undertaken by as a national effort involving scientists across the country.

Distinguishing combustion characteristics in rotten fuels and organic layers.

Rotten fuels and organic layers can contribute significantly to the amount of smoke produced and effects on soils and vegetation. The minimal flaming and considerable smoldering combustion associated with the burning of rotten wood and the organic layer is poorly understood. Currently, the two major fuel consumption models (e.g. Consume 3.0 and The First Order Fire Effects) use empirically based equations or simplified physically based models with empirically generated coefficients to calculate rotten wood and organic layer consumption with mixed results. Improved characterization of the rotten material, duff to capture the bulk density, depth, percent mineral soil content, and type of material will be important to improving the understanding of combustion and heat transfer and fire emissions.

The Fuel Characteristic Classification System (Ottmar et al. 2007) requires rotten woody fuel loading and organic layer depth, percent rotten, and derivation of organic layer to characterize these layers. Addition information is needed to distinguish the combustion of these fuelbed components. From work by Gurgel et al. (2007), it is believed the bulk density of rotten woody, species, size of the rotten particles, and improved bulk density of the organic layer will be required for improved combustion and heat transfer modeling. This project would take approximately 3-years and the RMFSL and the NRS would be the logical group to take on this study with their expertise in deep organic layer fire research and access to a burning table. In addition Dr. Eric Kasischke, University of Maryland, and Carlos A. Gurgel, University of Brasília would be important cooperators.

Dwellings and structure fuelbed components.

The Forest Products Laboratory and the Building and Fire Research Lab with their private sector cooperators have been leaders in the efforts to assess building materials and their ability to combust. They have found the surface fires carried by continuous fuels to a structure and firebrands may ignite structures depending on the materials and the design of the structures. They also found that structures can not be ignited by radiant heat flux levels typical to wildland fire when the flames are more than 100 feet away. However, most homes are constructed of combustible material and should be considered a wildland-urban interface fuelbed component capable of producing firebrands and radiant heat to ignite nearby fuels.

There are two problems to address. First buildings and dwellings can be considered a fuelbed component in their own right since once ignited, the radiant heat and firebrands emitted can ignite other structures or be a conduit to continue the fire spread. Fuel modelers need to account for structures as fuels and build fuelbed components that represent building and dwellings. During the Cold War, the Office of Civil Defense conducted fuel load assessments of several U.S. cities as a precursor to predicting the effects of nuclear explosion generated fires. Second, structures ignite depending on the construction material and design. Continued research on fire resistant material and design needs to continue as well as characterizing the flammability and firebrand production potential for native and exotic species that are the carriers of fire or producers of firebrands that can ignite buildings. Much work has already been completed in this area and 3-additional years of research will come close to completing this work. The Forest Products Laboratory (FPL), Rocky Mountain Fire Sciences Laboratory, Northern Research Station, and National Institute of Standards and Techonlogy are logical participants. This work has also been conducted in the southern portion of the U.S (east and west). It is a problem that should be coordinated nationally and have participation from across the country.

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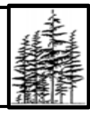
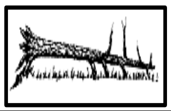
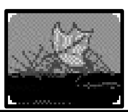
Stratum	Categories	Research Areas--Complex Fuels					Subelements		
		Moisture	Characteristics	Gaps	Rotten Duff	Structure	Transition	Heat transfer	Event dynamics
	Trees	X	X	X			X	X	X
Trees 	Snags		X				X	X	X
	Ladder fuels		X	X			X	X	X
	Primary	X	X	X			X	X	X
Shrubs 	Secondary	X	X	X			X	X	X
	Primary	X	X	X			X	X	X
Nonwoody 	Secondary	X	X	X			X	X	X
	All woody		X				X	X	X
	Sound		X				X	X	X
Woody 	Rotten	X	X		X		X	X	X
	Stumps		X				X	X	X
	Fuel accumulation		X				X	X	X
	Litter	X	X				X	X	X
Litter Lichen Moss 	Lichen	X	X				X	X	X
	Moss	X	X				X	X	X
					X				
	Duff	X	X				X	X	X
Ground Fuels 	Squirrel Middens						X	X	X
	Basal Accumulation						X	X	X
	House					X			
Structure 	Out building					X			

Fig. 4--Fuelbed strata and categories and suggested research areas.

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FIRE BEHAVIOR TRANSITIONS

Problem Description

Transitions in wildland fire behavior were identified as one of the five focal areas within Core Fire Science Framework developed for the Forest Service's Fire Research Strategic Program Area. Wildland fire is a dynamic phenomenon that responds to changes in the controlling variables of fuel, local weather, topography, and the atmospheric environment. These controlling variables change at various spatial and temporal scales. As a result, wildland fire responds and exhibits unsteady behavior at various scales. In this context, we define a fire behavior transition as the fire behavior response to a change in the controlling variables. This definition assumes that a fire will achieve equilibrium under a set of controlling conditions. The transition occurs between one equilibrium state and the next. Achievement of equilibrium is also scale dependent. Examples of fire behavior transitions which are important to public safety, ecosystem integrity and sustainability, and environmental quality include (1) transition from ignition to surface fire propagation (and from spread to no-spread), (2) structural ignitions from wildland fire, (3) transition from a surface fire to crown fire, including firebrand generation (4) transitions between flaming, smoldering, and residual smoldering combustion, and (5) transitions that involve convective interaction between the fire plume (flaming and non-flaming) and the atmosphere immediately surrounding it.

The goal of this problem is to develop a better physical description and understanding of how the controlling variables govern fire behavior transitions. Since heat and mass transfer processes are the building blocks of wildland fire, we seek to understand how the controlling variables influence these processes specifically. The importance of the controlling variables changes with scale thus changing the importance of the various processes. Initially, the focus of this problem will be on those processes that govern the transitions from surface fires to crown fires (fire in elevated fuels) and on those processes which govern propagation through complex fuelbeds.

Justification

It is well known that our current operational fire spread model was designed to model steady-state fire behavior. The equations in the Rothermel model do not explicitly describe heat or mass transfer and the applicable scale of the equations is fairly narrow when the full spectrum of fire behavior transitions is considered. Transitional fire behavior has often resulted in misses or near-misses for fire personnel. In order to better anticipate changes in fire behavior, we need to understand the transitions quantitatively, not just qualitatively. Many of the qualitative indicators of an incipient transition in fire behavior have been incorporated into the Fire Orders and the "Watch Out!" situations.

While most of the focus in wildland fire behavior research over the past 50 years has been on the "well-behaved" fire, transitional fire behavior has been addressed using a variety of approaches. A brief discussion of the research follows.

Current State of Knowledge and Inadequacy

Babrauskas (2003) provides an excellent compendium of information on the ignition of various materials. He presents a section devoted to forest materials (14 pages - includes forest floor, vegetation, and hay) and a section devoted to wood and related products (25 pages). A range of ignition temperatures for forest materials was reported by Babrauskas; recent work in living vegetation also reported a range of ignition temperatures for live vegetation samples (Fletcher et al 2007, Smith et al 2005). Babrauskas suggests that the various methodologies used in the tests may have influenced the results and the range of observed temperatures.

Ignition of wildland fuels by various mechanisms has been examined. The primary sources that have been considered include lightning, power line arcing, cigarettes, embers from a variety of sources, and smoldering combustion. Babrauskas summarized much of this work. The relative importance of fuel moisture, fuel particle size, wind, ignition source strength and other factors are examined. No physical models of ignition were presented in Babrauskas; Grishin and coworkers have examined ignition of litter fuels by various radiant fluxes and have developed physical models describing ignition (Grishin et al 1998, Grishin et al 2002). Further examination is needed to determine if the literature included in the compendium contains other physical models for ignition.

Ignition to Surface Fire Spread

The transition from ignition to surface fire propagation has been studied from both empirical/statistical and physical modeling approaches. Rothermel (1972) defined the concept of "moisture of extinction" and introduced a cubic equation to determine whether a surface fire would successfully propagate in shallow fuelbeds composed of dead foliage and grass fuels and small diameter (< 7.6 cm) wood fuels. Wilson's experiments examined marginal burning in moist dead fuel fuelbeds composed of milled, wooden sticks (Wilson 1982, 1985) and incorporated a better physical treatment of moisture content than Rothermel's earlier work. Wilson's work has been recently extended to examine marginal burning in live fuelbeds (Zhou et al 2005). This recent work included experimental work and numerical modeling of physical processes. Limited measurements were made using thermocouples and thermal imagery was collected for some of the experimental work. The numerical modeling was used to estimate the relative importance of radiation and convection on propagation under various experimental configurations. Statistical analysis was also used to develop a predictive model for fire spread success. This approach has previously been used in other fuel types – notably pinyon-juniper (Bruner and Klebenow 1979), Canadian (Beverly and Wotton 2007) and Australian fuels.

A steady-state physical model of fire spread in shallow litter fuelbeds was developed by Pagni and Peterson (1973) and compared with laboratory data from pine needle fuelbeds used to develop the Rothermel model (Rothermel and Anderson 1966). The Pagni model was recently extended to model fire spread in fuelbeds of vertically-oriented wooden stick fuels < 0.63 cm under various wind and slope configurations (Mongia et al 1998) and for chaparral fuelbeds (Koo et al 2005). While this model was not designed to describe transitional fire behavior, a limited test of its ability to successfully predict marginal fire spread in chaparral fuelbeds was promising (Weise et al 2005). An inherent limitation of a steady-state model is the inability to model acceleration of a fire's spread rate. Several authors have reported the sensitivity of spread rate to the size of the ignition source (Cheney et al 1993, Cheney and Gould 1997, Wotton et al 1991, Viegas 2004). A reformulation of Rothermel´s model (Sandberg et al 2007) predicts fire spread in heterogeneous fuelbeds by calculating heat sink separately for shrub, non-woody, and woody fuelbed components for inventoried rather than modeled fuelbed descriptions; enables spread modeling in live-fuel dominated fuelbeds; and explicitly includes litter in the heat balance calculations.

Structural Ignition Resulting from Wildland Fire

While structural ignition from wildland fire has occurred for a long period of time, focused attention on the problem has been sporadic. Work has occurred in the building fire arena that has focused on construction standards typically stimulated by large wildland-urban interface fires typically in California. Many of the construction standards that have evolved have focused on ignition of structures by firebrands or radiant heating from flames. Other management responses to structural loss from wildland fire have involved recommendations to remove vegetation near structures in order to modify the fire behavior in proximity to the structures.

One of the early attempts to model structural ignition from wildland fire is represented by the Structure Ignition Assessment Model of Cohen (1996). While the initial thinking behind this model was to couple models of structural fire with wildland fire models, the final model ended up as a heuristic model that drew on sound physical principles to derive an index-like rating of the propensity of a structure to ignite. Current work at the NIST Building and Fire Research Lab is focused on extending the Fire Dynamics Simulator equations to model fire spread through a heterogeneous environment made up of vegetation and structures. The multiphase model of Porterie et al (2007) has been applied to fire spread in the wildland urban interface.

Surface Fire to Crown Fire Transition

Because of its destructive potential, describing crown fires has long been a fire behavior research effort. The bulk of this work has occurred in coniferous forests. The research has matured from the initial approaches of identifying stand characteristics and environmental conditions associated with potential crown fire ignition (Fahnestock 1970, van Wagner 1977) to sophisticated modeling of crown fire spread. Cruz and others developed several models related to crown fires. In particular, a model to predict the transition from a surface fire to a crown fire was developed and evaluated (Cruz et al 2006a, b). Detailed physical modeling of fire spread has also been applied to surface to crown fire transition in shrubs (Morvan 2007, Tachajapong et al. 2008). Grishin and coworkers have also conducted experimental work and mathematical modeling of the transition of a surface fire to crown fire in conifers (Grishin and Perminov 1990, 1999). In most cases, validation data to test these models at full scale are not readily available. Utilizing the Fuel Characteristics Classification System, Schaaf et al (2007) have developed a model of crown fire potential based on the reformulated Rothermel model (Sandberg et al 2007).

Transitions between Flaming, Smoldering, and Residual Smoldering Combustion

Smoldering combustion is an important branch of combustion science that has received relatively little study in comparison to flaming combustion (Ohlemiller 2002). From a wildland fire perspective, smoldering combustion is important for several reasons which include the production of combustion products which are harmful if breathed and can obscure vision on highways. Smoldering combustion can also transition to flaming combustion which can result in rapid fire spread and the potential for damage. Recent fundamental research on smoldering combustion in wildland fuels has focused primarily on the characterization of the combustion products (Ward 2001) as well as the transport of these products by meteorological processes (Achtemeier 2005). The factors that influence fuel consumption in deep organic layers have also been studied and described by various statistical models (ie. Miyanishi and Johnson 2002, Otway et al 2007). Babrauskas (2003) and Ohlemiller (2002) produced summaries of literature on smoldering combustion with an emphasis on building materials; however, very little information on the transition from smoldering to flaming combustion was reported in either of these references. Frandsen and coworkers studied ignition and fire spread in organic soils from a heat transfer perspective; however, the transition from flaming to smoldering combustion was not studied. Carvalho et al (2002) and de Silva and others (2005) have provided dynamic numerical simulations of smoldering propagation and reported on field trials of smoldering logs, including analysis of extinction conditions and combustion rates.

Transitions that involve convective interaction between the fire plume and the atmosphere

The impact of convection columns on erratic fire behavior has been recognized for a long time. Down drafts from thunderstorms, or the fire itself, causing wind to flow in multiple directions which in turn causes a fire to spread erratically is a recognized wildland fire hazard. Ember production from plume collapse was reported for the Biscuit Fire as an impending danger. While this problem has been recognized, limited work examining this kind of fire/atmosphere interaction has occurred. Potter (2001) is a recent reference that encompasses this problem; however, detailed modeling or experimental work specific to fire are currently lacking. This topic is further developed in the Fire Environment Problem Analysis. Much of the work from Byram (1954) to the present on “blow-up” fires involves this type of transition. This transition is described in greater detail in the Fire Event Dynamics Problem Analysis.

Approach to Problem Solution

Ignition to surface fire spread

a. First, a model framework must be constructed that focuses again on the balance between heat source, heat sink, and heat transfer at the near equality between energy absorbed and energy required for ignition. Our current one-dimensional approach must be expanded to four dimensions in order to account for the shape and duration of heat source; the heterogeneity and spatial non-uniformity of fuelbeds to discriminate the absorption of energy by each fuelbed component and the loss of energy to the non-combustible environment; heat and mass transfer associated with the dynamics of moisture in the fuel; and specifically address the role of radiation, convection, and ignition point transfer within and external to the fuelbed matrix.

b. Second, each of processes in the framework model must be tested experimentally in small (laboratory) to medium (controlled field) and numerical (computer) experiments. Of special interest are the limits of fire spread from a) an ignition point, b) line source, and c) backing fire.

c. These model components will be added to what we now know and will know in future about pseudo steady state fire spread to incrementally add the capacity to model the probability of spread from ignition as well as the cessation of spread.

Surface fire to crown fire transition

a. Crown fire initiation: an energy balance problem that includes not only the convective input to the crown from a spreading flame front but that also includes the intensity and duration of radiant energy from post-frontal combustion; incident on an uneven pattern of variably-ignitable canopy surfaces; transported by convective eddies of various turbulences. Create a model construct based on the realistic complexity of the heat balance, and water mass balance rather than rely on observational and empirical evidence in simple cases.

b. Crown to crown fire propagation: expand on crown fire initiation by accounting for the energy contribution of the burning canopy and the efficiency of energy transfer from crown to crown where canopy closure is less than contiguous or where mixtures of combustible and non-combustible crowns are mixed

c. Canopy and surface fire reinforcement: include the radiation, ignition point transfer, and convective contribution of canopy fires to the propagation of surface fires.

Flaming to smoldering transition

a. Residual (independent) smoldering combustion: extend the numerical modeling and experimental approaches of Gurgel-Veras et al. to include logs of different conformation (e.g. rotten conifer logs) and deep organic (duff, moss, peat) layers. Test the individual hypotheses (such as oxygen diffusivity in moist semi-porous media) experimentally. Place the highest priority in modeling transition to residual smoldering in black spruce forests.

b. Piloted (i.e. short term, dependent) smoldering: model the physics of the pre-heating and pre-drying of heavy woody fuels and organic layers during flaming combustion that renders those fuel elements combustible in the soldering stage. This is a “bridge” model that accepts heat deposition accounting from a model of flaming combustion (especially residence time) and modifies the initial state of unburned fuels to some depth.

Transitions that involve convective feedback from collapsing plumes

See the Fire Event Dynamics Problem Analysis for this section.

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FIRE EVENT DYNAMICS AND FIRE-ATMOSPHERE INTERACTIONS

Problem Description

Definition: Fire event dynamics are the spatial and temporal patterns of the physical processes that govern wildland and prescribed fire events from the time of ignition to the cessation of the last smoldering ember, including the evolution of fire-fuel-atmosphere interactions that occur during these events.

Goal: The goal of fire event dynamics research is to improve our understanding of the fundamental, multi-scale, physical processes that take place during wildland and prescribed fires so that improved operational tools can be developed for predicting fire behavior and propagation.

Scope: Fire event dynamics research is focused on the influence of fire-induced buoyancy on the atmospheric circulations in the vicinity of wildfires and subsequent feedback to the fires; the interactions of the ambient mean and turbulent atmospheric flow fields with the physical environment surrounding fires; the impacts of local topography and fuel structure on the fire through their effects on the wind fields; and the way that fire influenced winds control the balances between convective and radiative heat transfer to unburned fuel (fire spread). The scope of fire event dynamics research specifically enhances our understanding of the thresholds and evolution of extreme, erratic, and transitioning fires; the spatial and temporal variability of multiple combustion environments within fire events; and the interaction of multiple fire fronts and/or convective columns.

Justification

Current operational fire behavior models do not accurately reflect the temporally and spatially variable physical environments in which fires can occur. Nor do they reflect many of the critical fire-fuel-atmosphere interactions that occur during fire events, which can have significant impacts on fire transitions and fire plume dynamics. For example, most operational fire behavior prediction systems have no way of accounting for or lack the appropriate parameterizations for the effects of ambient atmospheric turbulence on the spread of a fire or the transport and diffusion of heat, moisture, and pollutants within fire plumes. Current fire behavior prediction systems also lack appropriate parameterizations to account for interactions between multiple combustion environments that can add to the complexity of individual fire events. Significant advances in environmental monitoring technologies and high performance computing capabilities now make it possible to examine many of those physical fire processes and fire-atmosphere interactions that are integral to fire event dynamics but were impossible to examine 20-30 years ago. The development of the next-generation fire behavior prediction tools for the fire management community should take advantage of these experimental and computational advances as applied to fire event dynamics.

The multi-scale and integrative quality of fire event dynamics research makes it highly relevant to other physical fire process sub-elements within the Core Fire Science research portfolio of the Forest Service's Fire Strategic Program Area:

- Fire Transitions – Fire-fuel-atmosphere interaction research within the Fire Event Dynamics sub element can provide new insight into the relative importance of atmospheric mean and turbulent processes and atmospheric energetics in contributing to fire transitions (e.g. ignition to fire propagation transitions, structure ignitions in wildland fuel environments, ground to crown fire transitions, initiation of spotting, and interacting fire fronts).

- Combustion and Heat Transfer – Heat transfer via convection and the transport of fire brands are governed to a large extent by atmospheric mean and turbulent processes within the atmospheric boundary layer. Experimental and numerical modeling research within the Fire Event Dynamics sub-element can provide new insight into how turbulent heat fluxes and local-scale circulations contribute to the redistribution of heat during fire events.
- Fire Emissions – The development of new plume rise models for wildland and prescribed fire applications will require new insight into primary plume dynamics and the effects of atmospheric turbulence, atmospheric energetics, and multiple combustion environments on plume rise and growth. As such, Fire Event Dynamics research will provide much of the basic science underpinnings for the development of plume rise models for fire applications.

Current State of Knowledge

Fire event dynamics encompasses the relevant processes that leads us from an igniting spark to a large-scale conflagration, to a smoldering area and finally to an extinguished state. Central to fire events is how the relative importance of heat transfer mechanisms (conduction, convection and radiation) change across scales and how these heat transfer processes interact with the environment. For a given heat source intensity, radiation and conduction are fairly well understood; convective heat transfer and the interactions of fire with its environment have received less attention. Fortunately, convective heat transfer and fire atmosphere interactions can be addressed through the field of fluid dynamics.

The Navier-Stokes equations are the fundamental basis for the study of fluid dynamics and apply across a broad range of scales. If fire is viewed as a chemically reactive fluid flow, then the Navier-Stokes equations should provide an accurate description of a fire’s evolution in the gas phase. The National Institute of Standards and Technology (NIST) has utilized computational fluid dynamics in describing building fires for many years, although the confined nature of a building provides a limit to the scale of processes that are possible. For application to wildland fire events, Los Alamos National Laboratory has developed a CFD based modeling approach, FIRETEC, capable of describing the evolution of a fire event. Recently NIST has moved their CFD-based models to the outdoor environment to study fire dynamics in the wildland urban interface; the model is referred to as the wildland-urban interface fire dynamics simulator (WFDS). The Navier-Stokes equations have also been applied by Mahalingam and coworkers (both in the RANS and LES frameworks described below) to model transitions from no spread to spread and from surface to crown fire spread in laboratory fires using live fuels.

A shortcoming of the Navier-Stokes equations is that they do not form a closed system of equations (there are more unknowns than equations). Various solution techniques have been developed to alleviate this fault. The first, the Reynolds Averaged Navier-Stokes (RANS) equations employ an averaging operator to the equations that decomposes the flow variables to mean and fluctuating quantities where the fluctuating quantities can be viewed as turbulence. The behavior of these turbulence terms are then prescribed based on various theories and/or observations. The second technique, large eddy simulation (LES), assumes that we are modeling at the scale containing the most energy. In LES, instantaneous equations are spatially averaged. Additional terms, labeled sub-grid scale terms, represent processes occurring at small scales and are not directly resolved. Instead, suitable models are proposed to effect closure on the system of equations. This includes turbulent combustion in the gas phase. The third technique is direct numerical simulation (DNS). For DNS it is assumed that all important scales are represented and no sub-grid parameterization is required.

While DNS is popular in the engineering realm it is impractical for the problem of wildland fires as the range of scales is so vast (leaf scale up to landscape scale) that it is computationally impractical to model the entire environment at the smallest relevant scale. In LES the scale containing the most energetic eddies must be determined which requires knowledge of the turbulent energy spectrum which can vary across environments (forests would not have the same spectrum as grasslands). For RANS type modeling, it is important to know how the relative balance of subgrid scale processes changes based on the desired scale of the solution. For wildland fires a key process to understand is how the relative importance of convective and radiative heat transfer changes based upon the scale of interest.

Shifting to a fluid dynamics description of fire would also open the way to improved understanding of how the fire interacts with the atmosphere since the evolution of the atmosphere is also governed by the Navier-Stokes equations. Such coupling of fire and atmosphere would lead to an improved understanding of how atmosphere stability and moisture dynamics within the smoke plume influence fire behavior.

Approach to Problem Solution

Wildland fires are inherently complex events with processes spanning a wide range of space and time scales. A key component of this complexity that has been largely neglected is the potential for feedback between the fire and its environment. The Core Fire Science Team identified three focus areas for fire event dynamics research (as ranked in order of need by the team):

Characteristics, thresholds, and dynamics of blowup and plume-dominated fires

Fires release large amounts of heat and moisture into the environment, and the interaction of this heat/moisture with the three-dimensional, time dependent structure of the atmosphere governs the development of convective plumes and the flow fields surrounding the fires. While some atmospheric structures have been associated with blowup and plume-dominated fires (Haines Index, Byram's adverse wind profiles and Byram/Nelson's power of the wind versus power of the fire) little is known about the actual mechanisms governing this behavior. This is largely to do with the fact that much of the behavior of fires in these situations is tied to instabilities or fluctuations in the flow fields. The nature of these instabilities is tied to both the ambient atmosphere and the transient buoyancy of the fire-induced updraft. Advances in remote sensing (lidar) and computational fluid dynamics provide powerful tools for exploring this topic. Many of the advancements in our understanding of convective storms can be transferred to this problem as well.

Interactions of mean and turbulent ambient atmospheric winds and fluctuating fire-induced buoyancy-driven flows

At any time, atmospheric motions can be broken down into mean and fluctuating components. The fluctuating component consists of a spectrum of eddies of various sizes and amounts of energy, which is often referred to as turbulence. The heat released from a fire produces its own set of fluctuating buoyant updrafts that interact with both the steady and fluctuating components of the ambient winds. The rising turbulent gas from the fire feeds energy into certain size classes of eddies in the atmosphere and reorients them in ways that then feedback to the fire itself. Studies of turbulence in the atmospheric boundary layer have provided a great deal of knowledge on the basic turbulence structure of the atmospheric boundary layer under a wide range of conditions. Field experiments conducted in and around prescribed fires of various sizes and intensities would lead to a better understanding of how the fire modifies the atmospheric turbulence field and how this field in turn influences fire behavior. CFD-based models will provide a way to further study the behavior observed in the field experiments and will provide a basis for designing and optimizing the next generation field experiments.

Spatial and temporal variability and interactions of multiple combustion environments within a burn event

Individual wildfire events are often characterized by the existence of multiple areas of intense burning (referred to as combustion environments) at various locations across the landscape. These areas of burning generate convective plumes that can interact with each other and affect the overall atmospheric dynamics associated with a large burn event. The spread and behavior of a fire across the landscape (including transitions in fire behavior), in turn, depend but on the resulting atmospheric dynamics generated by the existence of multiple combustion environments. New fluid dynamics-based modeling and field experiments are needed to examine how multiple combustion environments across a landscape can contribute to changes in fire behavior. These modeling and field experiment efforts will provide the scientific basis for the development of parameterizations within operational fire behavior prediction systems that capture the impacts of interacting convective plumes in the atmosphere and their feedback to the individual combustion environments.

What key new knowledge must be generated?

A key component to implementing a fluid dynamics based fire model is developing a scale dependent description of turbulent process. The behavior of turbulence at 1 cm will be quite different than at 10 m as well the importance of turbulent heat fluxes relative to radiative processes.

What do we need to do first and foremost?

Design a range of field experiments, analytical simulation, and numerical simulation with the intent of collecting information on turbulence and fire behavior. Study will incorporate a variety of instrumentation and focus on a range of scales.

What specifically will we accomplish?

Develop a scale dependent description of turbulent fluxes that can be applied to both LES and RANS based CFD models of fire behavior.

How will we do it?

Expand upon previous efforts in fire behavior field studies, analytical solutions, and numerical simulations; and incorporate knowledge from atmospheric turbulence studies. The central hypothesis to test is that turbulent fluxes are an important factor in fire behavior and that their relative importance is scale dependent. Testing this hypothesis will require the collection of a substantial dataset ranging across fuel types and topographic conditions. This research will be of an interdisciplinary nature and require expertise in fuels, fire behavior, atmospheric science and computational fluid dynamics.

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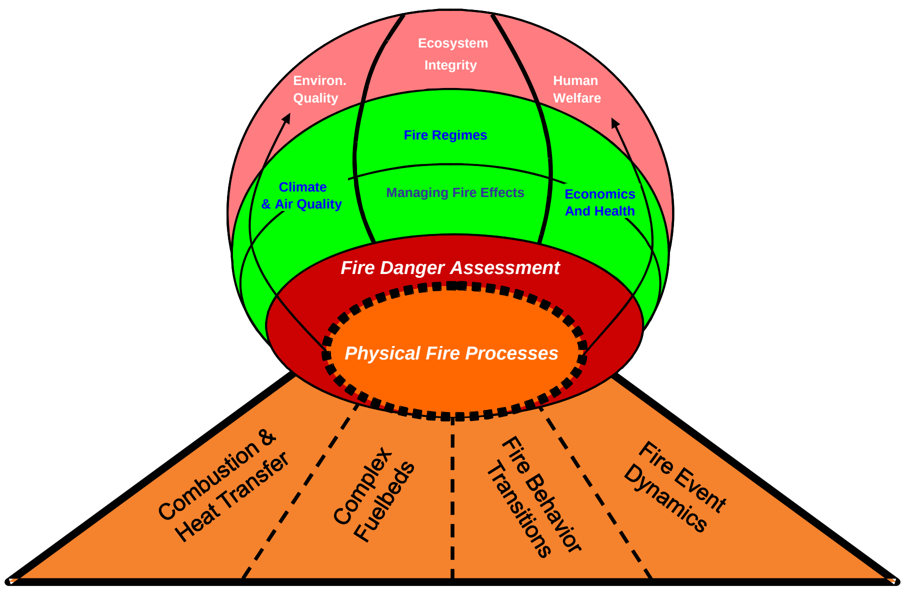
III. STUDY QUESTIONS

The preceding problem analyses are the results of a comprehensive review and revisions by a coalition of 28 invited wildland fire scientists participating in a scoping and writing workshop hosted by the Core Fire Science Portfolio Management Team in January 2008. The workshop discussion among participants also resulted in a list of “straw” study questions and hypotheses to address critical issues raised by each problem analysis. The full suite of study questions are presented here under the subheadings of the problem analysis sections, although many of the questions span the scope of two or more sections. Some were developed into complete study plans (chapter IV) for immediate funding requests from JFSP for FY08 and beyond.



PROBLEMS AND THEIR ASSOCIATED STUDY QUESTIONS

Combustion and Heat Transfer

Determining Ignition Requirements of Foliage and Fine Branch Material

What are the range of conditions over which heat transfer by convection and radiation can effectively ignite live foliage and fine branch material typically found in shrub and tree fuel complexes that support high intensity crown fire?

Numerical Simulation of Deep Fuelbed Test Burns and Comparison with Experimental Data

To what degree can results observed in deep fuelbed test burns be reproduced with the numerical fire model WFDS? What insights can be made about fundamental processes of wildland fire spread through comparison of experimental results and numerical simulations?

Rate and Residence Time of Combustion

Prediction of non-steady state fire behavior which incorporates transitions, and complex fuelbeds, and prediction of fire effects cannot be accomplished without being able to predict the rate of combustion and residence times in a mixture of fuel elements.

Numerical Experiments for Assessment of Conditions Required for Crown Fire Propagation

What are the conditions necessary for propagation of high intensity fires? (NOTE: This “Study Question” is of a larger scope than any of the 17 following Questions, so it is not a realistic candidate for immediate funding. Rather it is a description of a program of work that would address several Study Questions of a more typical scope)

Characterizing Attributes of Combustion Critical Fuelbed

The characterization of the each fuelbed component and spatially applying those attributes is important to improving our ability to understand and predict the physical fire processes of fire transitions, combustion, emissions, and fire event dynamics. Although advances in measuring and characterizing the fuelbed components have occurred during the past 5 years, there are several key fuelbed attributes that need to be added and studied if the physical process of fire behavior is to be advanced.

Complex Fuelbeds

Measuring and Modeling Convective Energy Transfer in Heterogeneous Fuelbed

What is the relative importance of the heat transfer mechanisms that govern transitions in flaming combustion in complex fuelbeds? Does the relative importance of convective and radiative heat transfer to fire spread in complex fuelbeds change from the scales of a litter fuelbed to an aerial canopy fuel?

Necessary Conditions for Crown Fire Initiation and Initial Spread

What combinations of surface fire and fuelbed characteristics and tall shrub and/or tree canopy fuelbeds and ambient weather are necessary to initiate torching; and what conditions and characteristics are necessary for initial crown-to-crown propagation?

Moisture Influence on Combustion in Complex Fuels

The lack of ability to quantify the effect of fuel moisture on combustion and fire behavior, especially that of live fuels and porous fuel elements, is a critical barrier to understanding and predicting fire behavior.

Determining Fuel Moisture Content of Combustion Critical Fuelbed Components

Fuelbed components contain various amounts of water that will dictate the ignition potential, heat transfer between fuel particles, and the eventual fire transition, behavior, and fire effects during a wildland fire. A more complete description of moisture content and the effects of fuel moisture in dampening combustion are required to advance the modeling of fires where dead and live fuels are involved.

A Spatially Explicit System for Fuel Modeling

Fundamental fire theory suggests that heat transfer mechanisms are highly dependent on the spacing between fuel elements and substantial evidence suggests that crown fire initiation and propagation are highly dependent on thresholds of horizontal and vertical continuity in the fuelbed. Additionally, variability in composition and size class distribution also plays a key role in fire behavior. At present no established means have been developed for characterizing or quantifying these important fuelbed properties other than with simple summary statistics.

Fire Behavior Transitions

Convective Plume Dynamics and their Impact on Fire Transitions

How do the atmospheric dynamics within and in the vicinity of individual or multiple interacting convective plumes impact fire transitions?

Fire Spread Thresholds and Flame Structure

How well can demonstrated fire spread thresholds be modeled and how closely is the observed flame structure and resulting convective ignition represented by large-eddy simulation?

Conditions Limiting Backing Fires

What physics fuelbed characteristics and conditions are necessary to maintain fire spread under no-wind or backing conditions?

Fire Event Dynamics

The Plume Dynamics of High Intensity Fires

What are the characteristic atmospheric circulations and convective heat transfer processes that occur in the vicinity of high intensity wildland fires?

Airflow in the Vicinity of a Fire

What is the flow in and near a wildland fire? Are there fundamental differences in the flow and dynamics in low and high intensity fires?

Interaction of Multiple Fire Fronts

Fire propagation on a landscape in non-uniform fuelbeds or where natural or managed barriers occur, prescribed fires, and flanking fires always involve fuels that are preheated by more than one flame source; and often are reinforced by the interaction of multiple convective cells. These accelerations of fire intensity and spread rate must be predicted using improved algorithms that account for multiple sources of heat flux and propagating flux ratios.

Improving Wind Forecasts for Fire Behavior Predictions

What methods can be used to extend mesoscale forecast winds to finer scales and resolution to benefit fire behavior models?

Investigating Causal Relationships between Fire Behavior and the Atmosphere

What case studies can be designed to test hypotheses on the role of atmospheric effects (inside and outside the fire's convective plume) on fire behavior metrics such as intensity or rate of spread and vice versa?

WORKSHOP PARTICIPANTS

In addition to the portfolio team, the workshop participants included:

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DISPOSITIONS

The portfolio team considered all of the study plans in this chapter in light of the need to propose those of highest priority for funding by the Joint Fire Science Program. This disposition section provides the considerations for their status.

Measuring and Modeling Convective Energy Transfer in Heterogeneous Fuelbeds

Study Questions -- What is the relative importance of the heat transfer mechanisms that govern transitions in flaming combustion in complex fuelbeds? Does the relative importance of convective and radiative heat transfer to fire spread in complex fuelbeds change from the scales of a litter fuelbed to an aerial canopy fuel?

Current Status of Study -- The estimated cost of this large, complex series of studies which includes field experiments such as the International Crown Fire Experiment and the recent Fireflux effort is $2.5M per year involving several scientists. While the work described here is on the critical path to the full physics fire model, we have decided to seek other avenues for funding since this currently exceeds the capabilities of the Joint Fire Science Program. We will work to identify other funding sources such as the Department of Homeland Security's grants program and the National Science Foundation to fund this research.

Improving Wind Forecasts for Fire Behavior Predictions

Study Question -- What methods can be used to extend mesoscale forecast winds to finer scales and resolution to benefit fire behavior models?

Current Status of Study -- While this study is critical to improving our ability to predict fire spread at fine spatial scales, the Portfolio Team does not feel that the study falls within "Core Fire Science". The need for high resolution prediction of wind flow over complex terrain crosses many disciplines beyond fire behavior. Recognizing its importance to existing and future fire spread models and the need for a replacement to Wind Wizard which is not a predictive model that includes meteorology, we will work with the study authors to identify other suitable funding sources such as the Department of Homeland Security or the Environmental Protection Agency.

Studies Related to Convective Plume Dynamics and Fire-Atmosphere Interactions

A total of six study questions related to convective plume dynamics and fire-atmosphere interactions were submitted to the Core Fire Science Portfolio Team for inclusion in the JFSP Science Advancement Plan:

- Measuring and Modeling Convective Energy Transfer in Heterogeneous Fuelbeds
- Convective Plume Dynamics and their Impact on Fire Transitions
- The Plume Dynamics of High Intensity Fires
- Airflow in the Vicinity of a Fire
- Interaction of Multiple Fire Fronts
- Investigating Causal Relationships between Fire Behavior and the Atmosphere

These proposed study questions address a number of research priorities identified in the Complex Fuelbeds, Fire Behavior Transitions, and Fire Event Dynamics problem analyses. While submitted as separate study questions to the Portfolio Team, all of them essentially address those physical processes that govern (1) the evolution of the atmospheric environment within and in the vicinity of areas of convection and (2) the feedback of the ambient and fire-induced atmospheric environments onto actual fire behavior. The research methodologies described in the study questions call for numerical modeling efforts (CFD-based, large-eddy-simulation and coupled fire-atmosphere models) and fire event field experiments with *in situ* instrumentation that both can advance our fundamental understanding of the spatial and temporal patterns of convective/radiative heat transfer and airflow during different types of fire event scenarios.

Because of the complexity of these overlapping but individually submitted studies, the significant resources needed to effectively carry them out, and the current allocation of National Fire Plan (NFP) funding to address some of the proposed elements in these studies, the portfolio team is recommending that they be combined in some fashion and then submitted for potential future JFSP funding in FY 2009 and beyond to augment the current support from the NFP. The portfolio team recognizes the relevance of these studies in addressing many of the critical atmospheric processes important for fire behavior prediction.

STUDY QUESTIONS

Determining Ignition Requirements of Foliage and Fine Branch Material

Study Question

What are the range of conditions over which heat transfer by convection and radiation can effectively ignite live foliage and fine branch material typically found in shrub and tree fuel complexes that support high intensity crown fire?

Observations of actual shrub and tree crown fires and of deep-fuel (>1 m vertical depth) laboratory experiments indicate non-steady flame extensions into adjacent fuels. This suggests a significant convection heat transfer contribution for crown fire spread. Some historical and current research has examined the relative contribution of convection and radiation as heat transfer mechanisms for fire spread in wildland fuelbeds. This body of work consistently points to the necessity of convection (flame contact) for flame propagation. However, most of this research was based on shallow uniform fuelbeds (< 1 m vertical depth). Current work by Fletcher and coworkers at Brigham Young University has examined the ignition properties of several western shrub plant species by exposing individual fuel particles to a convective heat source. Unpublished experiments (data on file) have investigated the efficacy of radiation as an ignition source for single particles. Some studies have examined the potential of standardized testing equipment such as the cone calorimeter as tools to determine time to ignition and heat release rates for vegetation samples. However, convective versus radiative contributions to heat transfer in these experiments have not examined live and dead fuels. As a consequence, we lack a reliable physical model describing the ignition of a single fuel particle and a group of particles.

Problem Identification

This question falls within the heat and mass transfer problem analysis.

Hypotheses

Reliable fire spread modeling and particularly the modeling of shrub and tree crown fires requires a greater understanding of the heat transfer and combustion processes (sub-grid model scale).

> H1. Shrub and tree canopy fuelbed ignitions resulting in active spreading crown fire require convection heat transfer from flame contact.
>
> H2. The volumetric pyrolysate production rate determines the ignition/flammability limit in fuelbeds where fuel particles cannot independently sustain flaming.

Study Direction

> Due to the unreliability of directly measuring convection heat transfer, several experiments will be designed to investigate the sufficiency of radiation heat transfer and the heat transfer required for fuel ignition. This provides the basis for computationally estimating the convection heat transfer.

1. Using a large (1m x 1m) high temperature (~1000^o C) radiant panel, single fuel particle and fuel particle clusters will be exposed to radiant exposures comparable to actual flame fronts. Fuel particle thermal measurements in association with physical model development will determine if radiation is sufficient for sustained fire spread.
2. Using a convection heat source, measured foliage temperatures and mass loss of live and dead foliage will provide a quantitative description of the requirements for fuelbed ignition.
3. Using a large (1m x 1m) high temperature (~1000^o C) radiant panel, a range of dead fuel volumes and bulk densities will be radiantly exposed to determine if the resulting volumetric pyrolysate mixture reaches the piloted ignition flammability limit without first initiating adjacent to a fuel particle surface. The experimental length scale must be large enough to produce increasing pyrolysate density with flow through the fuel volume.

Specific Outcomes

- Experimentally determining the resulting fuel particle temperatures from radiant exposures and the thermal requirements for live and dead fuel ignition provide the basis for computing the conditions that require convection heat transfer for sustaining fire spread in canopy fuels. The results of this investigation provide the basis for modeling the radiation and convection heat transfer necessary for sustained shrub and tree canopy fire spread and thus the basis for reliably modeling active spreading crown fires.
- Experimentally determining the existence of volumetrically produced piloted flammability limits provides important information for understanding how fire spread thresholds occur particularly for predominantly live canopy fuelbeds.

Numerical Simulation of Deep Fuelbed Test Burns and Comparison with Experimental Data

Study Question

To what degree can results observed in deep fuelbed test burns be reproduced with the numerical fire model WFDS? What insights can be made about fundamental processes of wildland fire spread through comparison of experimental results and numerical simulations?

Background

A large number of deep fuelbed test burn experiments have been carried out at the Missoula Fire Lab over the last five years. The intent of these experiments has been to examine fundamental mechanisms in fire spread in deep fuelbeds. Deep fuelbeds are fundamentally different in character from the surface fuelbeds used in the development of the Rothermel fire spread model, with lower bulk density, larger gaps between fuel elements and substantially greater vertical depth. An important difference between these experiments and previous ones with shallower vertical profiles is that the flame interface can be examined more easily. Preliminary results from these experiments suggest that flame contact, enhanced by fine scale fluctuations in flame geometry, plays a key role in fire spread. As the size of these fluctuations increases with bed depth due to buoyancy-induced turbulence, the propagation of the fire appears to be highly dependent on bed depth. This suggests a higher dependence on convective heat transfer than has been considered in previous work, which emphasizes radiative heat transfer. While these experiments have been informative and may provide important insights into the nature of fire propagation in vegetation canopies, they are in some ways incomplete. First, it is unclear the extent to which observed outcomes have been influenced by the boundary conditions and other associated characteristics of the experimental apparatus (i.e., enclosure affects due to wind tunnel walls, etc). Second, it is unclear the extent to which inferences from these experiments can be generalized to larger (more realistic) scales, or to situations in which larger scale heterogeneity exists within the fuelbed. CFD models, such as WFDS, are capable of addressing different means of heat transfer and are useful in identifying the underlying mechanisms occurring in particular fires, as well as boundary effects. They also provide a natural means of testing inferences at different spatial scales through simulation experiments. There is thus a potentially fruitful avenue of research that can be carried out using existing experimental data and numerical experiment. An important question pertains to the resolution used in the numerical simulation: in general the spatial resolution in the model is typically larger than that of the individual flames. To what degree is it necessary to capture the flame geometry? An interesting aspect of this project is that it is a win-win to all parties regardless of the outcome. In the event that the numerical experiments are able to consistently reproduce the empirical experiments, the inferences of the empirical experiments can be extended via numerical simulation to larger scales and situations of higher fuelbed complexity that would otherwise be difficult to carry out experimentally. In the event that the numerical model does not reproduce experimental results, new insights will be gained which will help advance numerical modeling of fires.

Problem Identification

This problem falls under the heading of the combustion and heat transfer problem analysis, but also has meaningful linkages to the complex fuelbeds and fire behavior transition analyses..

Hypothesis

Recent work emphasizes the importance of convective heat transfer in fire spread in discontinuous fuelbeds. However, convection is by nature a three dimensional process. In the development of the Rothermel model, the vertical heat flux is assumed to be negligible, lead to one-dimensional horizontal (parallel to the direction of fire spread) heat transfer. This assumption is not, strictly speaking, appropriate for sufficiently deep fuelbeds. In sufficiently deep and heterogeneous fuelbeds it is necessary to include the fully three dimensional heat transfer (convective and radiative) in order to model the fire behavior. Use of a detailed CFD model in conjunction with observed experimental data will provide invaluable insights as to the mechanisms of convection (including artifacts of boundary conditions) and of the balance and dynamics between radiation and convection in these experiments. Note that in the transition to established flame spread in deep fuels, heat transfer in the vertical direction is likely to be dominant in the higher fuels. For simplicity, the physical processes during transition are not investigated at this time.

Study Direction

In collaboration with Forest Service researchers, data from the deep fuelbed experiments will be compiled and organized for systematic comparison with numerical simulations. Careful measurements of the experimental apparatus and other relevant components will be used to set up the numerical experiments. An initial subset of experiments which span a range of different conditions will be selected for numerical simulation. Comparative and diagnostic analyses will be carried out to determine where simulation and empirical experiments agree and disagree.

Specific Outcomes

A large number of empirical experiments will be matched with corresponding numerical experiments. The fine scale nature and abundance of opportunities for comparison between numerical simulation and experimental results will undoubtedly result in an improved understanding of some of the key mechanisms in fire spread in deep fuels. The results of this work can also be used to determine the shortcomings and scope of application of the Rothermel model in a more quantitative way. The numerical experiments can used to compare the magnitudes of the horizontal and vertical heat fluxes (both convective and radiative). The validity of extending the conclusions of the laboratory based investigation to field-scale fire behavior will be assessed via numerical simulations of consistent field scale fires. Insights gained will be critical in future developments in core fire science.

PROJECT REQUIREMENTS AND STATUS OF WFDS: The CFD model to be used in this project is called WFDS. This model is and extension of NIST’s Fire Dynamics Simulator (FDS) to include vegetative fuels. FDS is a well established tool for structural fires and has its own visualization tool which greatly facilitates its use. Preliminary simulations of the deep fuelbed laboratory experiments conducted by the Missoula Fire Laboratory have been made. Some modifications to WFDS will be needed after a full understanding of the Missoula experimental configuration and fuel-type are obtained. However, these modifications are likely to be minor as

WFDS has been used to simulate burning tree experiments in NIST's large fire laboratory. While these experiments were of single trees, the physical scale of the experiments and the fuel types (in the fine fuels) are similar to the deep fuelbed experiments at the Missoula Fire Lab. WFDS simulations of flat fuelbed experiments (similar to those conducted by Rothermel or Catchpole) have also been conducted.

Given the above, it is expected that after an initial start-up period of relatively intense effort by both NIST and USFS personnel most of the running of WFDS to simulate the deep fuelbed experiments (the first objective) will be conducted by USFS personnel. The interpretation of the results and comparison to the deep fuelbed experiments will be conducted jointly (the second objective). Simulations of field scale scenarios to test if the observed trends in the laboratory experiments do hold at the field scale will be conducted jointly by NIST and USFS personnel. Thus, the overall simulation effort will be essentially evenly split between NIST and USFS personnel. This project is expected to require three years of effort (including reports and archival papers). It is important to note that NIST personnel are not fully funded. NIST's level of effort would require approximately $200,000 a year. A corresponding annual funding amount would be required from the USFS to complete this project.

Rate and Residence Time of Combustion

Study Question

Residence time of all stages combustion in all fuel categories and conditions

Prediction of non-steady state fire behavior which incorporates transitions, and complex fuelbeds, and prediction of fire effects cannot be accomplished without being able to predict the rate of combustion and residence times in a mixture of fuel elements.

Problem Identification

This study question derives from problem of combustion and heat transfer, but is necessary for solution of the problems of transitions, complex fuelbeds, and fire event dynamics

Hypotheses

Residence time is a function of fuel element size, condition, and overall combustion efficiency.

> H1: The primary upper limit on combustion rates in fuel elements larger than 3 mm thickness is the thermal conductive diffusivity native to the material.
>
> H2: Combustion rate is further limited primarily by oxygen availability first, and energy input second.

Study Direction

Laboratory studies to assess the thermal diffusivity (i.e. the rate of thermal penetration) of large woody fuels under a wide range of moisture contents (hypothesized to be unimportant) and heat input (hypothesized to be of little importance); measuring the thickness of the heated shell at intervals during preignition; compared to theoretical analysis of a heated cylinder governed solely by the thermal diffusivity of cellulose and to numerical simulations.

Combustion-oven experiments limiting oxygen; laboratory studies in compact (i.e. limited convection) fuelbeds; and numerical simulation experiments; compared to field observation.

Laboratory tests of current numerical simulations of smoldering propagation.

Specific Outcomes

- Determination of the length of time required to heat a sufficient shell of solid fuel before ignition when heated by radiative and convective flux
- The thickness (i.e. mass of shell heated) at ignition; the rate of combustion (diameter reduction) of coarse fuels
- The “effective heating number” for small fuel elements.

Numerical Experiments for Assessment of Conditions Required for Crown Fire Propagation

Study Question

What are the conditions necessary for propagation of high intensity fires?
(The scope of this study question is larger than any of the 17 other questions, so it is not a realistic candidate for immediate funding. Rather, it is a description of a program of work that would address several study questions of a more typical scope)

Background

High intensity fires (mostly crown fires in tall shrubs, conifer forests: see chapter III for complete definition) constitute one of the most serious fire issues, significantly affecting fire fighter safety, destruction of property and threatening ecosystem integrity in many areas. Yet, our fundamental knowledge of these phenomena continues to be limited. We recognize from empirical evidence and limited theory that the propagation of high intensity fires is often dependent on a number of interrelated conditions (e.g. adequate continuity within the fuelbed, wind speed, and heat flux). Many of these conditions are highly nonlinear in their interactions with fire, exhibiting marked threshold-like behaviors, where a small change in a particular condition may effect a large change in outcome. However, identification of these thresholds and how they interact with each other is extremely difficult; experiments carried out in a laboratory setting are often difficult to scale to the real world environments of high intensity fires, and field experiments carried out in the real environment are hampered by limitations in instrumentation, variability in conditions that complicate comparisons between experiments, and do not allow repeatable experiments to be conducted. An additional complication that influences both experiments at lab scales and field experiments is that fire propagation seems to be quite dependent on the spatial configuration of the fuels, the nature of the fire (dimensions and intensity of the flaming front) as it encounters the fuels in question, and on the timing with which events unfold. These temporal and spatial influences are cross-scale in nature, with events that have already happened (such as a tree that just torched) continuing to influence events ahead of them (e.g. through an accelerated flaming front due to an increased flux of radiative and convective heat), and thus involve complex spatial and temporal autocorrelations or dependencies that are not easily untangled or controlled for in statistical analyses.

One promising avenue of research would be to employ the physics-based fire research models such as those developed at NIST, LANL, and UC Riverside to carry out exploratory analyses, across a range of fuel and environmental conditions, to attempt to determine where key threshold behaviors might exist, and to see if these can be generalized or simplified in some way. The advantage of this numerical simulation approach is that inputs can be much more robustly standardized between experiments and that the complex interactions of the various factors involved are explicitly dealt with by the self-determining nature of these physics based models. Thresholds in various factors identified through these numerical experiments could then be tested and assessed in physical laboratory experiments and/or targeted field measurements for further study.

Problem Identification

This problem falls under the heading of the combustion and heat transfer and fire event dynamics problem analyses, but also has meaningful linkages to the complex fuelbeds and fire behavior transitions problem analyses.

Hypotheses

The propagation of high intensity fire likely requires not one, but several different conditions to be met; when one or more of these conditions fails to be met, the propagation of a high intensity fire will substantially change. The exact nature of these conditions is to be determined through exploratory work and is thus not specified here. The focus of the numerical experiments will be to identify thresholds in different factors, and the relative magnitude of those factors, in determining whether a fire continues to propagate or not.

Study Direction

The approach to solve this problem would entail a series of numerical experiments, to be carried out by both LANL and NIST, in collaboration with Forest Service researchers. Other parties could be included in certain aspects of the project as needed. A series of fuels and meteorological inputs would be assembled, and environmental conditions defined, such that numerical simulations could be carried out using several different models in a complementary fashion. The purpose of this collaborative and complementary modeling framework is that the combination of various approaches, and focus on different length scales would provide an opportunity for corroboration and additional insights that could arise from the two models, both of which have unique capabilities, strengths and weaknesses. There would be some degree of replication in the fuels inputs (and other factors as needed) to provide for ensemble simulations to facilitate generalization and to strengthen inferences from the study. In a given simulation a high intensity fire would be initiated (with some large initial heat flux) and then allowed to burn unimpeded for some period until its forward propagation was not simply an artifact of the initial ignition. Once this propagating front was established it would then be subjected to a number of different conditions (e.g. change in horizontal or vertical fuel continuity, wind speed, etc). Each simulation would be evaluated as to whether the fire continued to propagate or not. It is envisioned that the experiment might entail two or more phases, in which a preliminary set of simulations might be used to identify promising avenues of exploration and subsequent simulations might address a particular avenue in greater detail. In this manner, thresholds in particular conditions, and interactions with other conditions, could be teased out and analyzed. Each such relationship would then provide a context for future physical (laboratory) experiments, field measurement, or additional, more detailed, numerical simulation, or some combination thereof. In this manner the complex dynamics and dependencies involved in the propagation of high intensity fire could be systematically addressed.

Specific Outcomes

A number of positive developments would arise from this experiment. The first such outcome would be a stronger inter-institutional collaboration. If funded this experiment would represent one of the first large scale collaborations between NIST, LANL and USFS research. It would establish a basis from which numerous productive endeavors could unfold in years to come. Specific outcomes would involve a specification of the key requirements for propagation of high intensity fire, the ranges of conditions under which propagation continues, and analysis identifying potential areas where inferences gained from this experiment could be extended or validated by subsequent physical (empirical) laboratory or field experiments. An additional outcome of this project would be that procedures would be developed by which numerical simulations from various physics-based fire research models could be easily assembled, visualized, analyzed and compared. This is a necessary requirement of true collaboration and provides a pathway for synergistic and rapid development, trouble shooting and problem solving.

Project Requirements

This project is large in scope and will undoubtedly lead to a number of tangible advances in our understanding of high intensity fire. The inter-institutional collaboration outlined in this project is unprecedented and demands more than token support. At present the funding that has been made available to these world class modelers has been extremely limited. Unfortunately it can be impossible to foster productive collaborations between institutions in an environment in which there are no resources to do so. This is counter productive and disadvantageous to the Forest Service, which, lacking in its own expertise in these areas, benefits greatly from the work of both institutions. Both institutions have unique capabilities and expertise which is complementary in nature and it is important to establish a working situation where these institutions can afford to work together and with the USFS to bring new capabilities to address this complex problem. The magnitude of the problem of high intensity fires, and the lack of progress in this arena that has been made by the Forest Service alone despite decades of recognition of the inadequacies of current operational modeling approaches, necessitates a vision in which the pie is big enough for the problem to be reasonably addressed. We thus request funding of at least one million dollars per year for a period not less than three years. It is important to realize that the computational requirements of this project, which entail numerous detailed simulations, are considerable, and that these resources are not generally available gratis even within NIST and LANL. In most cases, use of supercomputers and experimental infrastructure is charged to researchers at these labs at a high premium. It is likely therefore that this budget would be more than reached in in-kind contributions just of computer and experiment resources alone. The expertise and experience of these researchers is largely irreplaceable in this solution of this problem.

Characterizing Attributes of Combustion Critical Fuelbeds

Study Question

The characterization of the each fuelbed component and spatially applying those attributes is important to improving our ability to understand and predict the physical fire processes of fire transitions, combustion, emissions, and fire event dynamics. Although advances in measuring and characterizing the fuelbed components have occurred during the past 5 years, there are several key fuelbed attributes that need to be added and studied if the physical process of fire behavior is to be advanced.

Problem Identification

This science question derives from complex fuelbeds problem analysis, but its solution is also necessary to complete the combustion and heat transfer, and fire behavior transitions analyses.

Hypotheses

The flammability, fuel area index, output, and ladder fuel continuity are four critical variables needed for improved heat transfer, fire transitions, and event dynamics for improved fire behavior modeling. These are variables that need quantification and improved techniques for measurement.

H1 (FC1): Species of live shrubs and grasses contain various concentrations of accelerate or fire retarding chemical compounds thus increasing or decreasing the threshold for surface rate of spread and intensity.

H2 (FC20: Fuelbed depth and gap quantification between fuelbed components can be rigorously quantified through new measurement protocols in conjunction with LIDAR or other electronic instrumentation signatures to advance surface fire behavior and fire transition modeling.

H3 (FC3): The thin 1/16 of an inch outer shell of fuelbed components controls the flame envelope and can be represented as a unitless index and quantified through a relationship between satellite, LIDAR, or other electronic instrumentation signatures.

Specific Outcomes

FC1. Develop a flammability and heat output index for key fuelbed components at various moisture contents for the United States.

FC2. Develop protocols for measuring fuelbed depth and gap continuity between fuelbed strata for forested and shrublands of the United States.

FC3. Develop an instrument, measurement protocols, or modeling capabilities to estimate fuel area index of all fuelbed components.

Study Direction

The fuelbed characteristic studies will be a combination of laboratory and field efforts. A combination of efforts from engineers and foresters from the fire labs, technology centers, and other scientific sources will be required to complete these needs within 3 to 5 years.

FC1. The development of a flammability index for key species of shrubs and grasses will be a laboratory study with a small field component for validation. Samples would be collected and brought into the laboratory for chemical analysis and flammability tests. The information will be used to increase or decrease the surface fire behavior thresholds of rate of spread and intensity. This research will require 5 years and include staffs from laboratories with access to a burning chamber including from NIST, Missoula, and Riverside.

FC2. The development of a standard set of field sampling protocols for fuelbed depth and gap analysis will occur in a field setting. A literature review and discussions with scientists directing new research in the areas of heat transfer and fire transitions will determine options for sampling. Field investigations will determine the feasibility of using field measuring protocols or ground based LIDAR. The information gathered from this study would be used in better predicting surface fire behavior and the transition from surface fire to crown fire. This research will require 5 years and include an engineer and fuel scientists from the PWFSL, Missoula fire lab, Riverside fire lab and technology development centers.

FC3. A ground or aerial based LIDAR or improved Leaf Area Index instrumentation will be designed and tested that will provide accurate estimation of fuel area or a fuel area index for all fuelbed components within a fuelbed. This information will provide improved heat transfer calculations for the improved fire behavior fuel modeling. The work will require 3 years and involve an engineer at the Missoula or Riverside Fire Lab in cooperation with the Technology Development Centers.

Measuring and Modeling Convective Energy Transfer in Heterogeneous Fuelbeds

Study Questions

What is the relative importance of the heat transfer mechanisms that govern transitions in flaming combustion in complex fuelbeds? Does the relative importance of convective and radiative heat transfer to fire spread in complex fuelbeds change from the scales of a litter fuelbed to an aerial canopy fuel?

It is well established that convection and radiant heating contribute to energy transfer within a fuelbed. Current physics-based numerical models (i.e. Morvan and Dupuy 2001, Zhou et al 2005) and earlier physical models (i.e. Albini 1966, Pagni and Peterson 1973, Albini 1986) included terms for both convection and radiation. Albini formulated the model with the assumption that radiant heating from flames above the fuelbed is the dominant mode of heat transfer in crown fires.

In the 1960s and 1970s, dimensional analysis was utilized to identify a large number of dimensionless groups important to wildland fire behavior (e.g. Byram 1966). Since this time, little attention has been paid to designing laboratory experiments so that the laboratory phenomena would scale to the full-scale phenomena.

Actual partitioning of heat transfer in a fuelbed experimentally has seldom been attempted. In a series of early experiments using wooden cribs, McCarter and Broido (1965) determined the relative contributions by convection, radiation, and conduction. Nearly half of the heat of combustion left the area of the fire by radiation and nearly half of this energy originated from glowing embers. Shielding the unburnt fuel from the flames did not reduce the rate of spread. Convective heat transfer accounted for the remaining 50% of the heat of combustion. These measurements formed the basis for much of the later, subsequent modeling of fire spread. The International Crown Fire Modeling Experiment is perhaps the only field experiment in which both radiative and convective heat transfer have been measured in crown fires (Butler et al 2004). In this experiment, radiative transfer occurred over fairly long distances (60 m) and for a longer period of time; convective heat transfer occurred only seconds before ignition with the arrival of the flame front with temperature increase rates as high as 700 °Cs^{-1}. Recent laboratory experiments using deep fuels (Finney et al 2006) and live fuels (Zhou et al 2005, Tachajapong et al. 2008) have utilized thermal imagery to examine the distribution of hot gasses in the vicinity of unignited fuel.

Extensive work has examined wind flow through forest canopies (i.e. Meroney 2007).

Experimental studies have measured convective and radiative energy transfer within fuelbeds over distances ranging from < 10^{-1} m to 10^{2} m. Unpublished thermocouple data associated with laboratory fires in dead fuels reported in Catchpole et al (1998) and Weise and Biging (1997) could be used to estimate convection at the 10^{-2} m scale. While the experimental and modeling data exist for a selected set of experiments, no attempt has been made to synthesize the results across the range of distances just mentioned. In most cases, the fuelbeds have been relatively homogeneous (at some scale); however, the flow has not been characterized in all of these experiments using a common measure such as the Reynolds number or some turbulence measure. Using a physical fire spread model formulated to predict rate of spread in thermally thin, low porosity material such as a litter fuelbed, Pagni (1975) described the dominant heat transfer modes as functions of 2 dimensionless groups – the Reynolds number and the Stefan number.

Problem Identification

This crosses over at least 3 of the problem analyses.

Hypothesis

Convection is the dominant heat transfer mechanism that governs the movement of flaming combustion through complex wildland fuelbeds.

Study Direction

- Focus on spatial scales of convective heat transfer that are most important for (1) quantifying energy fluxes within fuelbeds and between fuels and the atmosphere and (2) fully describing the energetics involved in fire transitions. Spatial scales will range from centimeters to 10s of meters. However, convective heat transfer in vegetation layers resulting from surface or crown fires cannot be viewed in isolation from the larger scale atmospheric environment.
- The process of convective heat transfer (i.e. the transfer of heat due to turbulent diffusion and advection) during fires is dominated by buoyancy generated turbulence regimes. Taking a fluid dynamics approach to investigating convective heat transfer processes during fire events is a viable approach for quantifying the significance of convective processes in fire transitions and basic fire spread.
- Research related to convective heat transfer during fire events should include both modeling and field experiment oriented studies.
- Modeling studies of convective heat transfer processes should take advantage of current state-of-the-art large-eddy-simulation modeling systems available for examining fire-atmosphere interactions (e.g. FIRETEC-HIGRAD, WFDS, NCAR, UULES, WRF, etc.).
- New field experiments during actual burn events under different fuel types/conditions and topographic conditions are needed to gather observational data relevant to convective heat transfer. Field experiments should include high-frequency sensing instrumentation for measuring the buoyancy generated turbulence regimes that govern convective heat transfer processes within burn environments. If possible, take advantage of existing flux monitoring networks already set up for measuring fire-atmosphere interactions and convective heat transfer processes.
- Studies focused on convective heat transfer should be interdisciplinary in nature and not exclude expertise in boundary-layer meteorology and computational fluid dynamics.

This study should utilize existing data as well as generating new data. The general approach follows:

1. Synthesize existing Forest Service experimental data to look at balance between radiative and convective modes

2. Establish common protocols in new experiments to measure radiative and convective fluxes as well as fluid flow
3. Use lab experiments to look at flows at 10^{-2} - 10^{0}-m scale
4. Focus field experiments on the 10^{0} to 10^{3}-m scale
5. Compare measurements with model outputs

Testing of these hypotheses will be conducted in a variety of complex fuelbeds ranging from lab to field scale. Heat transfer mechanisms will be measured using appropriate flux sensors for it situ measurements and remotely using appropriate thermal imaging devices. Particle imaging velocimetry will be used to determine fluid flow characteristics at applicable scales. Similar thermal techniques will be utilized on larger scale fires (Zhou et al 2003). Because of limited ability to instrument experimental fires in a fashion that does not affect results, various combustion models and approaches to simulation of fire dynamics will be compared with experimental data and also used to estimate heat transfer components for conditions outside the range of the experimental data.

Given the broad range of flaming combustion transitions, testing this hypothesis should involve at a minimum of 5 FTE scientists (experimentalists and modelers) for a concerted 5 year effort with funding of $2.5M annually.

Specific Outcomes

Solution of this question will provide a basic understanding of the relative importance of radiant and convective heat transfer mechanisms necessary to develop a physically-based fire model in heterogeneous fuelbeds.

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Necessary Conditions for Crown Fire Initiation and Initial Spread

Study Question

What combinations of surface fire and fuelbed characteristics and tall shrub and/or tree canopy fuelbeds and ambient weather are necessary to initiate torching; and what conditions and characteristics are necessary for initial crown-to-crown propagation?

Hypotheses

- In addition to crown fire initiation and spread caused by convective energy from the spreading (propagating) flame front; crowning also occurs as a result of longer-duration irradiative and convective energy from post-frontal flaming and smoldering
- H1 Crown fire spread is materially affected by crown closure (horizontal gaps in the canopy), mid-canopy wind speed, and crown depth as well as energy from the surface fire, foliar moisture, and crown base height.
- H2 Reaction efficiency and flame intensity in conifer canopies and in flammable shrubs can be predicted from canopy LAI and canopy depth, foliar moisture content, and some measure of “waxiness” or other flammability coefficient

Moisture Influence on Combustion in Complex Fuelbeds

Study Question

The lack of ability to quantify the effect of fuel moisture, especially that of live fuels and porous fuel elements, on combustion and fire behavior is a critical barrier to understanding and predicting fire behavior.

Current practice is to accept the obviously false assumption that live fuels diffuse moisture and limit combustion similarly to the empirically observed effect of moisture in fine dead fuels. The problem is compounded in complex fuelbeds that are a mixture of several live and dead components. Techniques for rapidly measuring moisture content in both live and dead fuels and new approaches for modeling and remote sensing fuel moisture are also inadequate.

Problem Identification

This science question derives from the problem analysis of complex fuelbeds, but its solution is also necessary to complete combustion and heat transfer, and fire behavior transition analyses.

Hypotheses

Fuel moisture content is regulated by material type, percent of decay, and whether it is live or dead and can be measured directly, modeled, or remote sensed to better model the important fundamentals of fire behavior including heat transfer, fire behavior transition and fire event dynamics.

Fuel moisture affects combustion in several ways. It serves as a heat sink in limiting the threshold of ignition, rate of spread, and transition from flaming to smoldering and from smoldering to extinguishment. It also participates in combustion to decrease or "dampen" the intensity and in some cases slow the combustion rate.

> H1: The rate of liberation of moisture from fine grasses and forbs during flaming combustion is so rapid that it is not limiting to the rate of combustion (after ignition) of those fuels, consequently:
>
> H2 : All of the effect, i.e. heat sink, of fuel moisture and grasses is manifested in the heat absorbed during resignation, thus limiting the threshold condition for spread and the rate of spread of surface fire, but not the flaming intensity or any of the smoldering processes.
>
> H3 The energy to liberate physiologically bound moisture from uncured woody fuels and from live woody fuels (B2b) is approximately twice that of the latent heat of evaporation of free water, thereby reducing the moisture content above which no combustion or spread can be expected, doubling the influence of live fuel moisture in establishing the moisture of extinction. (this is NOT an endorsement of the current procedure for calculating "moisture content at extinction", but only of the general concept that at some moisture content the heat absorbed by unburned fuels is less than the heat of pre-ignition)

Study Direction 1

These three hypotheses can be tested simultaneously through a controlled set of laboratory experiments observing fire behavior and elemental analysis of combustion products; paired with a set of numerical experiments such as in FIRETEC.

H4 (G4d) and (G4c), (H4d), (H4c): Moisture content of semi-porous fuelbed layers is seldom limiting to the rate of consumption, at least until free (vis-à-vis gravitation) water is present. That is, the moisture diffusivity is always greater than the thermal diffusivity and the oxygen diffusivity (against a combustion-product gradient) within the porous fuel. Therefore, duff moisture latent heat of evaporation will affect the threshold of extinction but not the rate of smoldering progression.

Study Direction 2

These hypotheses can be tested simultaneously through a controlled set of laboratory experiments observing fire behavior and elemental analysis of combustion products; paired with a set of numerical experiments such as in the 2-dimensional numerical model by Gurgel et. al. (2007) and the field observations by Carvalho et al (2006) and by conducting additional field and laboratory experiments in deep feather moss or peat fuelbeds.

Specific Outcomes

1. Provide the knowledge to incrementally improve surface fire spread models by adding more fuel-component specific and realistic algorithms for a) moisture damping and b) heat sink coefficients based on updated published information, improved theory, and new experimental evidence.
2. Provide the basis for predicting moisture influence on fire behavior, including combustion rates and limits in all stages of combustion for incorporation into the next generation of fire models.
3. Utilize numerical simulation, laboratory experimentation, and field validation approaches in a coordinated effort to upgrade our 30-year old approach to modeling moisture effects on fire behavior.
4. Provide the basis for investigating and solving the influence of live and porous-fuel moisture on transitions to extreme fire behavior and extinguishment; complex-fuel fire modeling, and event-scale variability in fire behavior.

Determining Fuel Moisture Content of Combustion Critical Fuelbed Components

Study Question

Fuelbed components contain various amounts of water that will dictate the ignition potential, heat transfer between fuel particles, and the eventual fire transition, behavior, and fire effects during a wildland fire. **A more complete description of moisture content and the effects of fuel moisture in dampening combustion are required to advance the modeling of fires where dead and live fuels are involved. Moisture content is extremely variable and depends on the type and size of the fuel, the amount and type of decay, and whether it is live or dead. Although the absorption, movement, and release of moisture in sound, dead wood can be well modeled, it is poorly understood for live fuels, woody fuels with decay, and organic layers.** New techniques for rapidly measuring, remote sensing, or modeling moisture content in both live and dead fuels prior to ignition and new approaches for modeling fuel moisture movement during the pre-ignition and flaming combustion stages are needed.

Problem Identification

This science question derives from the complex fuelbeds problem analysis, but its solution is also necessary to complete the combustion and heat transfer, and fire behavior transition problem analyses.

Hypotheses

The absorption, movement, and release of bound and unbound water within live and dead fuels before combustion is dependent upon the (1) material and size of the material; (2) percent and type of decay; () position in the fuelbed; (4) frost zone location; and (5) weather variables such as total precipitation and duration, relative humidity, temperature, and wind speed. These are the variables that will be required to consider when developing direct fuel moisture sampling procedures and modeling or sensing moisture content remotely.

H1 (FM1): The sampling technique and number of samples required to determine fuelbed component moisture content within an acceptable error for predicting fire behavior will be dependent upon material type, size, arrangement, location in the fuelbed, percent decay, and whether it is live or dead.

H2a (FM2): A simple probe for easy direct measurement of moisture contents between 0 and 400 percent can be developed to represent 1) live tree crowns, stems, shrubs, grasses leaves, needles, mosses, and lichen; 2) dead sound and rotten woody material; 3) litter, and d) duff.

H2b (FM2): Synthetic materials that mimic the absorption and liberation of moisture can be used as surrogate moisture content indicators for live and dead fuelbed components.

H3 (FM3): The moisture content of specific fuelbed components can be modeled using moisture diffusion theory and knowing the live or dead material type, location in the fuelbed, percent decay, and weather variables.

H4 (FM4): Direct moisture content or a representative moisture or greenness index can be determined from remote sensed reflectance for live and dead fuelbed components critical to fire behavior prediction.

Specific Outcomes

FM1. Develop a set of standard sampling protocols for the key fuelbed components that drive fire transition including a) live tree crowns, stems, shrubs, grasses leaves, needles, mosses, and lichen; b) dead sound and rotten woody material; c) litter, and d) duff.

FM2. Develop and test a moisture probe or improved moisture content surrogates for use in accurately and easily determining moisture content fuelbed components that drive fire transition including a) live tree crowns, stems, shrubs, grasses leaves, needles, mosses, and lichen; b) dead sound and rotten woody material; c) litter, and d) duff.

FM3. Develop a physically based model for predicting moisture diffusion and the resulting moisture content of fuelbed components that drive fire transition including a) live tree crowns, stems, shrubs, grasses leaves, needles, mosses, and lichen; b) dead sound and rotten woody material; c) litter, and d) duff.

FM4. Investigate the use of remote sensing tools for improving estimations of moisture content for fuelbed components that drive fire transition including a) live tree crowns, stems, shrubs, grasses leaves, needles, mosses, and lichen; b) dead sound and rotten woody material; c) litter, and d) duff.

Methodology

The fuel moisture content studies will be a combination of laboratory and field efforts. A combination of efforts from engineers and foresters from the fire labs, technology centers, and other scientific sources will be required to complete these needs within 3 to 5 years.

FM1. The development of the standard fuel moisture field sampling protocols will be a field approach. A literature review will determine the best sampling techniques. Samples would be collected and oven dried over the course of a fire season in several areas of the country to estimate fuel moisture variation and determine the number of samples required. The information gathered from this study would be used in the modeling task. This research will require 5 years and include staff from the PWFSL and Riverside.

FM2. A moisture probe or moisture content surrogates will be designed and tested that will provide accurate fuel moisture content values for live and dead fuels. Valuable features of available duff moisture, wood moisture meters, and research on 10-hour fuel moisture sticks may be used to begin the investigation and design. This work will require 3 years and involve an engineer at the Missoula or Riverside Fire Lab in cooperation with the Technology Development Centers.

FM3. A sophisticated modeling approach based on the physics behind moisture diffusion would be a laboratory study undertaken by an engineer based at the Missoula or Riverside Fire Labs. The task will take approximately 5 years to complete. Data collected from the fuel moisture techniques research in part 1 could be used for calibration and testing.

FM4. Investigation of remote sensing techniques for evaluating fuel moisture changes in live fuels will be a field effort. New and improved remote sensing tools would be investigated for their potential for estimating fuel moisture content for both live and dead fuels. Moisture content sampling coordinated with the standard fuel moisture sampling protocol task would be undertaken to calibrate and develop algorithms that will enable the remote sensing of moisture content directly or the development of a moisture index. This task will require an engineer and field crews over the course of five years from the Missoula and Riverside laboratories.

A Spatially Explicit System for Fuel Modeling

Study Question

There is an important need for a fuel modeling system that is capable of representing spatial information across a range of spatial scales. Fundamental fire theory suggests that heat transfer mechanisms are highly dependent on the spacing between fuel elements and substantial evidence suggests that crown fire initiation and propagation are highly dependent on thresholds of horizontal and vertical continuity in the fuelbed. Additionally, variability in composition and size class distribution also plays a key role in fire behavior. At present no established means have been developed for characterizing or quantifying these important fuelbed properties other than with simple summary statistics.

Problem Identification

This problem falls under the heading of complex fuelbeds problem analysis.

Hypothesis

Spatial relationships within the fuelbed, such as distances between fuel clumps, and the size class distribution of gaps or voids, play a critical role in fire initiation and propagation.

Specific Outcomes

A three-dimensional fuel modeling system will be developed which extends an existing but preliminary system, FUEL3D. More species and vegetation types will be modeled and the system will be advanced incrementally closer to an operational system. A system to parameterize the model from field data will be refined and broadened.

Study Direction

A three-dimensional spatially explicit fuel modeling system, FUEL3D incorporates allometric theories and fractal geometry to produce detailed and quantitative representations of fuels from the scale of a needle clump to individual trees to landscapes. At present the model has been developed for Ponderosa pine but will need to be modified for other species and vegetation types (shrubs, grasses, etc). FUEL3D is specifically designed to provide inputs for state of the art fire behavior models developed at LANL and at NIST. The development of spatially explicit fuel models and related research represents a significant step in the advancement of the field of fire science and will enable robust and quantitative evaluation of fuel treatment alternatives and related fire management strategies.

The speed at which this system will move forward will depend on the level of support attained. Ideally funding would support one GS-12 PI at 50%, one or more full time programmers, one GS-11 analyst, and a crew of 5 field technicians for two or more years, as well as software and some equipment.

Convective Plume Dynamics and their Impact on Fire Transitions

Study Question

How do the atmospheric dynamics within and in the vicinity of individual or multiple interacting convective plumes impact fire transitions?

Current operational fire behavior models do not accurately reflect the temporally and spatially variable physical environments in which fires can occur. Nor do they reflect many of the critical fire-fuel-atmosphere interactions that occur during fire events, which can have significant impacts on fire transitions and fire plume dynamics. For example, most operational fire behavior prediction systems have no way of accounting for or lack the appropriate parameterizations for the effects of ambient atmospheric turbulence on the spread of a fire or the transport and diffusion of heat, moisture, and pollutants within fire plumes. Current fire behavior prediction systems also lack appropriate parameterizations to account for interactions between multiple combustion environments that can add to the complexity of individual fire events. New research is needed to (1) improve our understanding of the effects of ambient atmospheric turbulence regimes and multiple combustion environments on convective plume dynamics and potential transitions in fire behavior and (2) develop improved operational predictive tools for fire behavior that account for those atmospheric processes that can lead to transitions in fire behavior – including scaling in size and intensity, as well as fire growth and acceleration.

Problem Identification

This study question is derived from the fire event dynamics and the fire behavior transitions problem analyses.

Hypotheses

H1: Atmospheric boundary-layer turbulence regimes associated with individual or multiple interacting convective plumes during fire events contribute to transitions in fire behavior (e.g. surface to crown fires).

H2: Individual and multiple interacting plumes generate significant turbulence anisotropy in the atmospheric boundary layer via buoyancy and shear effects that can lead to near-surface turbulent circulations conducive to fire transitions.

H3: Turbulent heat fluxes in the vicinity of the convective plume environment are an important factor in fire behavior and fire transitions, and their relative importance is scale dependent.

H4: Ambient atmospheric turbulence regimes associated with frontal passages can interact with convective plumes to enhance fire transition probabilities.

Study Direction

Wildland fires are inherently complex events with processes spanning a wide range of space and time scales. Key components of this complexity that have been largely neglected are the potential for feedback between individual or multiple, interacting convective plumes and the atmospheric environment, and the resulting atmospheric boundary-layer turbulence regimes that may contribute to transitions in fire behavior.

At any time, atmospheric motions can be broken down into mean and fluctuating (turbulence) components. The turbulence component consists of a spectrum of eddies of various sizes and amounts of energy. The heat released from a fire alters this spectrum by feeding energy into certain size classes of eddies, which in turn interact with the entire spectrum. Numerical modeling and observational studies of turbulence in the atmospheric boundary layer have provided a great deal of knowledge on the basic turbulence structure of the atmospheric boundary layer under a wide range of conditions. Much less is known about how individual or multiple, interacting convective plumes associated with individual or multiple fire events across the landscape can alter the atmospheric boundary-layer turbulence environment surrounding these fire events. Little is also known about how ambient boundary-layer turbulence regimes associated with events like frontal passages interact with convective plumes to alter near-surface turbulence environments. It is this turbulence environment that contributes to erratic fire behavior and the potential for significant transitions in fire behavior.

New fluid dynamics based modeling and field experiments are needed to examine how atmospheric boundary-layer turbulence regimes generated during burn events can contribute to changes in fire behavior, especially transitions in fire behavior. These modeling and field experiment efforts will provide the scientific basis for the development of parameterizations within operational fire behavior prediction systems that capture the impacts of convective plumes on near-surface turbulence and fire transitions.

Methods

1. Design and carry out a series of comprehensive field experiments during prescribed burn events under a variety of fuel types/conditions that focus on atmospheric boundary layer turbulence and fire behavior (e.g. FireFlux). Data analyses from these field experiments should include a description of the turbulent kinetic energy (TKE); TKE components; turbulence spectra; turbulent heat, moisture, and momentum fluxes; and radiation to go along with the typical fire behavior and fuel related descriptions. Data collected from these field experiments will provide turbulence regime validation data for the numerical modeling components of this study.
2. Design and carry out a series of fluid dynamics based numerical modeling studies focused on the field experiments in item #1, using the current state-of-the-art large-eddy-simulation modeling systems available for examining fire-atmosphere interactions (e.g. FIRETEC-HIGRAD, WFDS, NCAR, UULES, WRF, etc.). Observational data from item #1 will be used to validate model results. Analyses of simulation results will focus on (i) descriptions of the atmospheric boundary-layer turbulence regimes associated with the convective plumes that characterized the burn events in item #1 and (ii) on descriptions of turbulence regime impacts on observed fire behavior.
3. Design and carry out a series of fluid dynamics based numerical modeling scenarios focused on fire transitions using the current state-of-the-art large-eddy-simulation modeling systems available for examining fire-atmosphere interactions. Scenarios will include different fuel types/conditions, topography, multiple combustion events, and mean atmospheric conditions (including frontal passages) in order to assess the sensitivity of fire behavior and the occurrence of fire transitions to convective plume development and associated turbulence regimes that develop from individual or multiple combustion events.

4. Identify specific atmospheric scenarios and scale-dependent turbulence regimes that are most conducive to transitions in fire behavior during individual or multiple burn events across the landscape.
5. Based on the identified scenarios in item #4, develop new parameterizations of turbulence impacts on fire behavior and fire transitions that can be implemented in operational fire behavior prediction systems.

Specific Outcomes

1. Improved understanding of the atmospheric boundary-layer turbulence impacts on fire behavior and potential transitions in fire behavior.
2. Improved fire behavior and fire transition predictions via new fire behavior prediction systems that incorporate parameterizations of convective plume impacts on atmospheric boundary-layer turbulence.

New observational data sets that are critically needed for validating coupled fire-atmosphere models and large-eddy-simulation models applied to fire-atmosphere interactions.

Fire Spread Thresholds and Flame Structure

Study Question

How well can demonstrated fire spread thresholds be modeled and how closely is the observed flame structure and resulting convective ignition represented by large-eddy simulation?

Crown fires in tree and shrub canopies often demonstrate complex thresholds for active spread that involve wind, slope, and fuel structure. Laboratory experiments have identified thresholds for horizontal spread that depend on fuelbed depth, horizontal fuel gaps, and slope. Fire dynamics models using Large Eddy Simulation (WFDS, UCR-LES) have not been tested against these data to see if these observed behaviors can be duplicated. Flame contact and fine-scale structure was found by earlier experimentation to be necessary for ignition of fuels across discontinuities with and without wind, suggesting that specification of sub-grid process in simulation models is crucial to fire modeling. This study will expand the laboratory studies to generate data on spread thresholds for comparison with modeling. By modeling the laboratory-scale experiments we will be able to understand 1) if these models contain sufficient detail (at grid and sub-grid scales) to model ignition and wildland fire thresholds, and 2) extend the scale of computational results to field-scale fuelbeds and crown fires not possible to explore in the laboratory.

Problem Identification

This study question derives from the combustion and heat transfer, and fire behavior transitions problem analyses.

Hypotheses

Fire spread thresholds are consistent among wind-driven and slope-driven fires at laboratory scales (indicating a strong role of fuel-fire geometry in fire spread).

Large-eddy simulation models contain sufficient detail on flame structure to model ignition of fuels near the combustion interface and represent fire spread thresholds observed in laboratory experiments in live and dead fuelbeds.

Flame structure, including entrainment, vorticity, and velocity, generated by laboratory experiments are well modeled by the large eddy simulations.

Large-eddy simulation models can be extended to field-scale crown fires.

Study Directions

Laboratory experiments using live and dead fuels will be continued in a wind-tunnel to generate data on fire spread thresholds similar to those involving slope. Similar experiments will be performed using a wind tunnel that can be tilted to include both wind and slope effects. Variables include horizontal fuel gaps, fuelbed depth, and wind speed. Flame deflection occurs in the presence of wind and allows spread across areas of fuel discontinuity in a manner that is geometrically similar to the effect of slope (tilting the fuel-bed toward the flames). However, physical differences are likely to be significant, including the axis of flame tilt relative to the gravity force and the vertical dimension of the fuelbed gaps. Model performance in the wind-driven laboratory fires is critical to complementing the comparisons of slope-driven fires.

Laboratory studies in the absence of wind will be extended to deeper fuelbeds (2.5 meters) to examine flame structure that is generated with longer flow-lengths in spreading fires. Increased turbulence and flame vorticity is expected, leading to increases in convective heat transfer because of higher flame velocity and eddy sizes. The results are expected to increase the ability of fire to spread across gaps in the fuelbed. When possible, techniques such as Particle Imaging Velocimetry (PIV) and Thermal PIV will be used to visualize fluid flow.

Computational studies will be conducted using two fire dynamics models (WFDS, UCR-LES) to compare model results with threshold and heat transfer assumptions with all laboratory data. Physical descriptions of the laboratory experiments (fuels, environmental conditions, ignition configuration) will be created and the fires modeled in three dimensions. Heat transfer mechanisms in the models will be studied by monitoring convection and radiation histories at various points within the bed and comparing them with data collected from the laboratory. Fire spread thresholds will be compared between models and experimental data. Provided that the model performance is comparable with laboratory scale-data, numerical experiments will be performed for fires of much larger scale, including crown fires with fuelbed depth of ~10-20m.

Specific Outcomes

- The combination of laboratory and numerical experiments will inform and verify model formulations and engender confidence in using fire dynamics modeling by Large Eddy Simulation as research tools in understanding high-intensity fires that cannot be easily studied at their natural scale

Furthermore, the flame structure at along the combustion interface within the fuelbed and its scalability from laboratory-scale to field-scale will be described

Conditions Limiting Backing Fires

Study Question

What physics fuelbed characteristics and conditions are necessary to maintain fire spread under no-wind or backing conditions?

The extent of free-burning fires in many fuel types including hardwood litter, moss, and lichen depend on the ability to sustain combustion through the night when humidity is highest and wind is calm or counter to fire spread. Prediction of aerial fire extent under these conditions requires a fundamentally different scale and physical mechanism of heat transfer than does a flaming front aided by wind under dry conditions. We do not know the threshold of fuel load continuity, fuel moisture, and fuel characteristics necessary to maintain fire spread.

Problem Identification

This study question derives from the problem of transitions, but is necessary for solution of the problems of combustion and heat transfer, and fire event dynamics

Hypothesis

Sustained fire spread in litter, moss, and lichen relies on heat transfer (mostly radiation, but secondarily by convection) at the centimeter scale. Continuous fuelbreaks or interruptions as small as 3 centimeters during nighttime conditions is often enough to limit fire size. Interruptions may consist of scarce fuels, compacted (such as by having been walked on) or the presence of coarse woody debris.

Study Direction

Develop a cm-scale fire spread transition model for fine surface fuels under marginal conditions. Use laboratory and field tests to test the moisture, loading, and continuity limits.

Specific Outcomes

- Understanding that leads to a fire spread model for hardwood and conifer litter, especially under no-wind or backing conditions.
- Understanding of the threshold requirements for expecting a fire to “overnight” in litter, moss, and lichen fuelbeds.

The Plume Dynamics of High Intensity Fires

Study Question

What are the characteristic atmospheric circulations and convective heat transfer processes that occur in the vicinity of high intensity wildland fires?

Current operational fire behavior models do not accurately reflect the temporal and spatial variability of the physical environments in which wildfires occur. Nor do they reflect many of the critical fire-fuel-atmosphere interactions that result in the complex fire transitions and plume dynamics associated with high intensity fires (HIFs). They are incapable of describing the atmospheric circulations and convective heat transfer, and therefore, fire behavior, in the vicinity of HIFs. The solution to the problem requires an understanding of the fundamental, multi-scale, physical processes that take place during fire events.

Significant advances in environmental monitoring technologies and high performance computing capabilities now make it possible to examine many of physical fire processes and fire-atmosphere interactions that are integral to fire event dynamics but were impossible to examine 20-30 years ago. The development of the next-generation fire behavior prediction tools capable of predicting HIF behavior and propagation should take advantage of these experimental and computational advances.

Problem Identification

This study question is derived from the fire event dynamics and the fire behavior transitions problem analyses.

Hypotheses

Pyroconvection (e.g. pyrocumulus and pyro-cumulonimbus) from high intensity wildfires and their impacts on fire dynamics and the ambient atmosphere

> H1: Fire-released moisture from high intensity wildfires has a significant impact on the dynamics and properties of convective plumes, including entrainment characteristics and vortex behavior.
>
> H2: Atmospheric circulations and associated features of convection columns generated during high intensity wildfires affect the behavior of these wildfires.

Fundamental dynamics of buoyant plumes from high-intensity wildfires

> H3: Convective plumes from high intensity wildfires, including their structure, the amount of entrainment that occurs, and associated vorticity/turbulence fields, depend on the ambient atmospheric conditions and topography.
>
> H4: The transient nature of high intensity wildfires affects the dynamics of convective plumes differently than plumes arising from steady sources.
>
> H5: Convective plumes from high intensity fires comprising a fire event can interact with each other and feed back on the behavior of these fires.

H6: Transient atmospheric events (e.g. frontal passages, sea-breeze circulations, thunderstorms) during high intensity wildfires can affect fire-atmosphere interactions and the structures of the convective plumes associated with these fires.

Study Direction

Pyroconvection (e.g. pyrocumulus and pyro-cumulonimbus) from high intensity wildfires and their impacts on fire dynamics and the ambient atmosphere

High-intensity fires produce not only large amounts of heat but also large amounts of water vapor, both from the evaporation of moisture contained within the fuel and from the chemical transformation of carbohydrates during the combustion process. Very little is known or understood about the role of this released moisture on the dynamics of plumes associated with high-intensity fires, although there is evidence that latent heat resulting from the condensation of this moisture can cause the plume to rise substantially higher in the atmosphere than would be expected simply due to the heating produced by the fire. The associated pyrocumulus (and in most intense cases, pyrocumulonimbus) clouds may transport smoke and other aerosols to great heights in the atmosphere, and the circulations associated with these features may impact fire behavior.

New research is needed to gain fundamental insight into the dynamics of pyroconvection from high-intensity fires; given the early stages of this area of research and the difficulty of observing these features, it is anticipated that this research will be numerical in nature, using state-of-the-art numerical models that can incorporate both plume dynamics from fires and the dynamics of moist processes that are typical of clouds.

Fundamental dynamics of buoyant plumes from high-intensity wildfires

The dynamics of buoyant plumes have been studied extensively in engineering and air quality contexts; however, the state of knowledge regarding the application of this knowledge to plumes arising from wildland fires – particularly high-intensity fires – is still in its early stages. High-intensity wildland fires represent dynamic, transient sources that can often possess unique characteristics. It is important to understand the fundamental aspects of plume dynamics that are found under these conditions, such as plume structure, entrainment characteristics, and vorticity/turbulence dynamics, and how these aspects of plume behavior depend on the ambient atmospheric conditions (e.g., wind and stability profiles, ambient turbulence, transient weather systems), as well as how they may impact fire behavior.

New research is needed to examine these fundamental properties, both using numerical modeling approaches and field experiments. In particular, a series of CFD-based modeling studies should be designed and carried out using current state-of-the-art large-eddy simulation (LES) models, and validated where possible with well-instrumented field experiments.

Methods

1. Design and carry out a series of comprehensive field experiments during burn events under a variety of fuel types/conditions that focus on atmospheric circulations and convective heat transfer within and in the vicinity of the fire environments. Measurements should take advantage of radar, lidar, thermal imagery, photogrammetry, tethered balloon soundings, and instrumented flux tower opportunities. Data analyses

from these field experiments should include a description of the ambient atmospheric circulations and turbulence regimes; the fire-induced circulations and turbulence regimes; heat, moisture and momentum fluxes; and radiation to go along with the typical fire behavior and fuel related descriptions. Data collected from these field experiments will provide much needed validation data for the modeling components of this study.

2. Design and carry out a series of fluid dynamics based numerical modeling studies focused on the field experiments in item #1, using the current state-of-the-art large-eddy-simulation modeling systems available for examining fire-atmosphere interactions (e.g. FIRETEC-HIGRAD, WFDS, NCAR, UULES, WRF, etc.). Observational data from item #1 will be used to validate model results. Analyses of simulation results will focus on descriptions of the fire-atmosphere interactions that occurred during the burn events in item #1.

3. Design and carry out a series of fluid dynamics based numerical modeling scenarios focused on high intensity fires using the current state-of-the-art large-eddy-simulation modeling systems available for examining fire-atmosphere interactions. Scenarios will include different fuel types/conditions, topography, multiple combustion events, and different ambient atmospheric conditions (including transient weather events) in order to assess the sensitivity of the behavior of high intensity fires to these variables.

4. Identify specific atmospheric scenarios that are most conducive to the development and sustainability of high intensity fires.

5. Based on the identified scenarios in item #4, develop new parameterizations of convective plume impacts on high intensity fire behavior that can be implemented in operational fire behavior prediction systems.

Specific Outcomes

1. Improved understanding of the atmospheric impacts on the behavior of high intensity fires.

2. Improved understanding of the role of fire-released moisture on the dynamics and properties of convective plumes from high intensity fires.

3. Improved fire behavior predictions of high intensity fires via new prediction systems that incorporate parameterizations of convective plume impacts on fire behavior.

4. New observational data sets that are critically needed for validating coupled fire-atmosphere models and large-eddy-simulation models applied to fire-atmosphere interactions.

Airflow in the Vicinity of a Fire

Study Question

What is the flow in and near a wildland fire? Are there fundamental differences in the flow and dynamics in low and high intensity fires?

It is recognized that fires and atmospheric flow feed back on each other to create many observed fire behavior phenomena, particularly in the vicinity of the fire. Recent studies (Clements et al 2008) have focuses atmospheric measurements to reveal quantitative measurements of fluxes and airflow in and near grassfires. Coen et al. (FROSTFIRE paper) and Clark et al (ICFME paper) have discussed extreme fire behavior phenomena detected by infrared imagery within crown fires. Early experiments in mass fires also examined flow in and around a high intensity fire (Palmer 1981, Countryman 1968). Carrier and coworkers (Carrier et al 1984, 1985) have also hypothesized wind flow associated with fire storms.

Problem Identification

This study question is derived from the fire event dynamics and fire behavior transitions problem analyses.

Hypotheses

H1. The flow in the vicinity of low intensity fires is described by a convective plume (over the fire if there is no ambient wind, ahead of the head of the fire if there is an ambient wind driving the fire), a stagnation region ahead of the fire front, and air descending into the base of the updraft from the rear. The convective plume may or may not block the ambient flow.

H2. The flow in a vicinity of a crown fire is significantly more complex. The release of heat from many burning elements unites into a larger scale convective updraft. The drag from the canopy influences the low level flow, possibly in decreasing degree as the biomass burns away.

Air and particles of incomplete combustion from the plume may recirculate back down into the fire.

The plume can block the ambient flow.

Study Direction

Collection and analysis of remote and *in situ* observations of wildland fires, both low and high intensity, along with complimentary numerical modeling studies. These observations may be planned (either prescribed fires or research fires) or fires of opportunity. A great deal of discussion must go towards defining a set of observations that can pin down the needed variables. Combined modeling and observations allows a holistic view of the evolving 3-dimensional structure of fire and airflow that neither can achieve alone.

Specific Outcomes

A conceptual picture of the flow in and near wildfires.

References

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Clements, C.B.; Zhong, S.; Goodrick, S.; Li, J.; Bian, X. Potter, B.E.; Heilman, W.E.; Charney, J.J.; Perna, R.; Jang, M.; Lee, D.; Patel, M.; Street, S.; Aumann, G. 2007. Observing the dynamics of wildland grass fires: FireFlux- a field validation experiment. Bulletin of the American Meteorological Society. 88(9): 1369-1382.

Coen, J.L.; Mahalingham, S.; Daily, J.W. 2004. Infrared imagery of crown-fire dynamics during FROSTFIRE. Journal of Applied Meteorology. 43:1241-1259.

Palmer, T.Y. 1981. Large fire winds, gases, and smoke. Atmospheric Environment 15(10/11): 2079-2090.

Interaction of Multiple Fire Fronts

Study Question

Fire Behavior Influenced by Multiple Flaming Fronts and Plume Interactions: Fire propagation on a landscape in non-uniform fuelbeds or where natural or managed barriers occur, prescribed fires, and flanking fires always involve fuels that are preheated by more than one flame source; and often are reinforced by the interaction of multiple convective cells. These accelerations of fire intensity and spread rate must be predicted using improved algorithms that account for multiple sources of heat flux and propagating flux ratios. Limited laboratory experiments of merging flame fronts have been conducted; however, only one study describing the effects of merging flame zones resulting from spot fire ignition has been found in the literature (Johansen 1984, 1987).

Problem Identification

This study question derives from the fire event dynamics problem analysis, but is necessary for solution of transitions, combustion and heat transfer, and complex fuelbeds analyses.

Hypothesis

Interruptions in fuelbed continuity are not effective at slowing overall spread rates (minimum travel time) or area burned unless the size of the fuel barrier perpendicular to the general rate of spread is orders of magnitude larger than the maximum flame length of the free-spreading fire front. The added travel distance around treated fuels is offset by a four-fold increase in rate of spread and doubling of flame lengths where flames coalesce in the lee of the fuel break

Study Direction

Modify spatial fire spread models to intensify the pre-heating rate and propagating flux ratio where multiple fire fronts coalesce. Compare simulated results to observed fire behavior in field trials. Numerical simulation compared to point-based models of propagation.

Specific Outcomes

Modification of spatial algorithms for fire spread around interruptions in fuel continuity; verification of theory through field observations; adaptation of propagation models such as Farsite and Flammap.

References

Johansen, R.W. 1984. Prescribed burning with spot fires, in the Georgia Coastal Plain. Georgia Forestry Research Paper 49. Macon, GA: Georgia Forestry Commission. 7 p.

Johansen, R.W. 1987. Ignition patters and prescribed fire behavior in southern pine stands. Georgia Forestry Research Paper 72. Macon, GA: Georgia Forestry Commission. 6 p.

Improving Wind Forecasts for Fire Behavior Predictions

Study Question

What methods can be used to extend mesoscale forecast winds to finer scales and resolution to benefit fire behavior models?

Among the variables forecast for fire weather, wind speed and direction are among the most important for fire behavior. The Office of the Federal Coordinator of Meteorology's Joint Action Group for National Wildland Fire Weather Needs Assessment (draft) identifies the spatial and temporal evolution of winds particularly in complex terrain as an urgent need. Currently, meteorological forecasts are routinely made at resolutions of 1-2 km and coarser. Even so, the wind speed and direction are among the variables with the highest errors. Meanwhile, increasing forecast resolution (from 4 km to 1 km) in standard mesoscale models such as MM5 failed to demonstrate increase the objectively-measured forecast skill (Hoadley et al. 2004). To fill this gap between needed resolution/skill and current capabilities, diagnostic operational tools [ref. WindWizard, etc.] have been applied to interpolate sampled winds to the sub-100 m scale needed to forecast fire behavior. These tools in turn have limitations arising from their inability to produce transient flow effects, effects of atmospheric stability and other thermal effects (such as solar heating of slopes). However, they run fast and can provide a faster than real time wind estimate.

Problem Identification

This study question is derived from the fire event dynamics, and the fire behavior transitions problem analyses.

Hypothesis

H1. Improved forecasts of winds in complex terrain, either through fine-scale numerical weather prediction or improved diagnostic tools, can improve modeled fire behavior.

Study Direction

A near-term, quick response research project that applies fine-scale numerical models (grid spacing < 100 m) to explicitly resolve winds in complex terrain can be applied in specific case studies to provide high resolution 4-dimensional "truth" data against which developing operational wind tools can be compared (rather than sparse weather station data). It can also be tested as a faster than real time forecasting tool, the output of which would be used in fire behavior models.

Specific Outcomes

Improved forecasts of winds in complex terrain and somewhat improved predictions of fire behavior, although this should be done in tandem with studies to improve understanding and representation of fire behavior.

References

Hoadley, J.L.; Westrick, K.; Ferguson, S.A.; Goodrick, S.L.; Bradshawo, L.; Wreth, P. 2004. The effect of model resolution in predicting meteorological parameters used in fire danger rating. Journal of Applied Meteorology. 42:1333-1347.

Office of the Federal Coordinator of Meteorology. 2007. http://www.ofcm.gov/jag-nwfwna/workingdocuments.htm

Investigating Causal Relationships between Fire Behavior and the Atmosphere

Study Question

What case studies can be designed to test hypotheses on the role of atmospheric effects (inside and outside the fire's convective plume) on fire behavior metrics such as intensity or rate of spread and vice versa?

Many explanations have been posed but not proven of a link between atmospheric conditions and fire behavior. The external atmospheric factors include (1) the structure of the ambient atmospheric environment (such as the vertical structure of the temperature profile (i.e. the 'lapse rate'), (2) vertical gradients in wind speed (i.e. 'vertical wind shear'), transience in strength or direction of air in the convective column (i.e. a change from updraft to downdraft due for example to the production of sufficient mass of precipitation, the deceleration of the updraft due to weakening of fire intensity, etc.), (3) effects of atmospheric turbulence (which here may refer to the almost random fluctuation of velocity, temperature, and scalar concentrations around their mean value or to coherent turbulent features), (4) local-scale, mesoscale or synoptic meteorological features such as frontal passage, shifting winds during the growth and decay of a pyrocumulus (the cloud produced by a growing fire convective column), solar heating of slopes, drag from vegetation, or descent of air from upper levels. Internal fire-atmosphere interactions can be described in terms of fire behavior such as bowing forward of firelines, fire vortices, and fingers of flame bursting forward from the fireline.

Shotgun approaches with numerical models testing the sensitivity to various atmospheric parameters have suggested some cause and effect relationships, but have not filled enough of the parameter space to lead to true understanding. The problem remains is that anecdotal accounts say "This caused That" and there is no established research to confirm or deny it. This work would explore what kinds of atmospheric feedbacks could be occurring and how important they could be. Any significant burning will produce some perturbation of the ambient atmosphere.

However, this change and possible interaction may not necessarily produce a significant change in the fire behavior, i.e. spread rate, intensity and spotting.

Problem Identification

This study question is derived from the fire event dynamics and fire behavior transitions problem analyses.

Hypotheses

> H1. For a fire in a given wind speed environment, a lapse rate close to the dry adiabatic lapse rate produces a higher intensity fire than more stable lapse rates because the buoyancy at elevations in the updraft is greater and thus the vertical velocity and acceleration in the updraft is greater, causing greater convergence into the base of the updraft, and thus faster fire spread at the head of the fire.

H2. Flames in crown fire flame fronts are vertical because the convective updraft caused by the fire blocks the ambient wind.

Study Direction

These studies include identification of priorities, perhaps based on safety impact, of fire behavior phenomena to be studied. Perform a hard-nosed literature review of the literature to distill leads on real phenomena. Testable hypotheses connecting cause and effect must be posed. Well-documented phenomena (with remote and in situ data if available) should be examined as case studies with collaboration of fire behavior specialists and atmospheric scientists. Numerical model experiments (fire behavior, weather, and coupled atmosphere-fire) should be designed to test the hypothesized relationship with specific case studies around which sensitivity experiments should be designed to isolate the cause and effect and estimate the sensitivity of the phenomena to the cause.

Specific Outcomes

- Confidence in cause-and-effect relationships between atmospheric phenomena and fire behavior phenomena.

Reference

Clements, C.B.; Zhong, S.; Goodrick, S.; Li, J.; Bian, X. Potter, B.E.; Heilman, W.E.; Charney, J.J.; Perna, R.; Jang, M.; Lee, D.; Patel, M.; Street, S.; Aumann, G. 2007. Observing the dynamics of wildland grass fires: FireFlux- a field validation experiment. Bulletin of the American Meteorological Society. 88(9): 1369-1382.

IV. IMMEDIATE (FY08) CFSPT FUNDING PRIORITIES AND DRAFT STUDY PLANS

CHOICE OF STUDIES RECOMMENDED FOR IMMEDIATE SUPPORT

All of the study questions in chapter III are worthy of support. Each represents fundamental improvement in Core Fire Science that would incrementally improve fire management decision support and form the scientific basis for the next generation of modeling systems. Obviously, choices must be made to select those that best fit the mission and capacity of the Joint Fire Science Program and simultaneously occupy the "critical path" to the Core Fire Science vision.

After the January 2008 workshop, the Core Fire Portfolio Management Team (CFSPT) selected from, combined, and revised four of the study questions for immediate consideration. Several characteristics stand out as the necessary and immediate focus because they so fundamentally limit our current approaches, or weaknesses if you prefer, in predicting fire behavior.

1. Better understanding and modeling the influence of live fuel moisture on combustion
2. Sharpening our knowledge of the requirements of ignition for foliage and branch material that initiates and sustains shrub and canopy fires
3. Accurate representation of complex fuelbeds using a spatially explicit fuel modeling system,
4. Modernizing our experimental and analytical methodology by employing numerical investigations of coupled atmosphere fuel structure influence on fire behavior.

The study questions identified in the previous paragraph were used as the basis for the development to five study plans. The first three studies require additional financial resources requested of JFSP beginning in FY08, and were submitted to the Board of Governors. The fourth and fifth studies (Numerical Investigation) have already been identified for full funding by the CFSPT using National Fire Plan funding.

List of Study Plans

Submitted for Joint Fire Science Program Funding

- Moisture Influence on Combustion in Live Fuels
- Determining Ignition Requirements of Foliage and Fine Branch Material
- A Spatially Explicit Fuel Modeling System

Full Funding by National Fire Plan Core Fire Science Portfolio

- Numerical Investigation of Coupled Atmosphere Fuel Structure Influence on Fire Behavior
- Description of Planned Work Performed by NIST to Support Two Study Areas

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APPENDIX: EXTERNAL REVIEW OF CORE FIRE SCIENCE ADVANCEMENT PLAN

The JFSP asked the Core Fire Science Portfolio team to execute an external review of this advancement plan by selected individuals. The team elected to solicit individual reviews, rather than a consolidated (panel) review, and also determined that it would be most appropriate to solicit reviews from both domestic (USA) and international partners. Seven reviewers were contacted and the four who responded are listed below:

- **Jim Gould—**Team Leader; CSIRO (Commonwealth Scientific and Industrial Research Organisation)(Australia) Forest Biosciences-Bushfire Dynamics Applications Group
- **Philip Omi—**Colorado State University
- **Domingas Xavier Viegas—**University of Coimbra (Portugal), Department of Mechanical Engineering
- **R. Gordon Schmidt—**U.S. Forest Service Fire Management (retired); Brookings Institution

A draft plan was sent to each reviewer on February 11, 2008, including instructions, questions, and apologies for the very short timeframe (2 weeks) we provided the reviewers for their response. The four questions we asked each reviewer to address are summarized below:

1. Is the tiered analysis (portfolios into elements; elements into contexts and perspectives; and finally, into study questions and hypotheses) a logical way to go?
2. Did each of the four problem analyses break down the problem into logical components?
3. The set of study questions were formulated with respect to one or more Problem Areas and/or contexts. Please assess them with respect to the following
   a) an important science question;
   b) a testable hypothesis that will answer (solve) the question;
   c) a reasonable study direction;
   d) relevance to ultimate outcomes (applications)
4. Please apprise us on how well we, as a community, were able to meet the challenge of leapfrogging to a few critical, do-able, proposed studies?

Reviewer comments and our reconciliation of them are presented here in two forms, each based on how we received and assessed the comments:

1. The narrative comments submitted by reviewers without reference to specific text, sentence, or paragraph within the plan are reconciled below in a generalized form; that is, we do not attribute comments to specific reviewers.[2]
2. Two reviewers (Jim Gould and Gordie Schmidt) provided specific comments in the margins of the plan, and we address these with respect to the specific portion of the plan to which they refer.

GENERALIZED COMMENTS AND RESPONSES

[2] Original copies of reviewer comments and narratives are on file with team leader Colin C. Hardy, and can be referenced to the team's generalized responses below if requested.

General comments, concerns, and commendations: Reviewers concur that the plan identified significant scientific gaps and suggests feasible approaches to address them. One reviewer notes, "The draft plan appears comprehensive and well thought-out." They all agree with the need to (finally) move out of the last 30 years and into the next 3-5. Additionally, they seem to agree with the Forest Service Fire and Fuels R&D External Review Panel that "fifteen years is too long" (to develop the next model). The team was commended for assembling such a distinguished panel of contributors during the workshop and study formulation phases. Regarding the team's decision to focus on fundamental physical fire processes and associated fuel questions, one reviewer felt we should NOT have eliminated fire emissions ("seems to be an important one and should not be dropped"), while another reviewer asks us to stay on task with our notion of core understanding: "I do not argue that they are important, only that they are not 'core;'" and, "While these may be 'core' to the profession I don't see them as 'core' to understanding combustion from which all must flow." Another reviewer notes: "I found difficulty in proposing a program centered on fire physics; it had always to be mixed with other aspects and objectives and so very often it lost its strength." Our response—we couldn't (and didn't) say it better! Although the fourth reviewer asked for more breadth and stronger linkages with the other portfolios, we reject that in the spirit of our deliberate attempt to anchor this fundamental work in areas we feel lie in the critical path to other elements dependent on this work.

Several reviewers commented on the critical need to involve stakeholders in all aspects of planning, implementing, and delivering this science. Our team concurs, and during early development of the concept of Core Fire Science, we brokered meeting time with the NWCG Fire Environment Working Team to vet our ideas (successfully). We were proud to host a wiring workshop for 28 national leaders in fire research. We're particularly encouraged by the enthusiasm with which the external reviews accepted our request to review the plan!

We like a concept suggested by one reviewer that suggests a transition phase approach to developing and adopting new modeling and models. He described three boxes; Black-box, comprised of current traditional models; Grey-box, integrating empirical models with physics-based models; and White box, comprising the future, fully-dimensioned physical models.

The reviewers noted some "lack of polish," and we couldn't agree more! As a review put it, "The document needs strengthening to reach its full potential…it should eventually prove to be useful and merit the considerable time and energy already invested." We submit this with both the expectation and the commitment to continue its development and refinement, independent of funding (or not). We anticipate the need to better describe our study proposals, if requested. As a strong, general comment, a reviewer tells us: "First, let me just say it is time to get on with it. The first draft of the core I reviewed was dated May 17, 2006, almost two years ago. It really is time to do something other than sending paper back and forth collecting ideas." Okay, here we go.

1. The tiered analysis—structure, efficacy, clarity: The strongest common element among the four reviews was the confusion we introduced by the (many) layers, or tiers, we presented. These tiers begin with the original Core Framework, which we included almost verbatim from the working framework document. In that, we begin with the strategic program areas (SPAs), one of which (Fire SPA) has five portfolios, and the Core Fire Science Portfolio is only one of those five. Then we noted five elements, including emissions, but follow by eliminating emissions from consideration without much explanation. In other words, why did we present the

emissions element at all if we new it would be excluded from this plan? The answer, simply put, is "full disclosure." That is, we went on record as having deliberately determined that, while emissions fit within the broader framework, the emissions work did NOT fit within the finer filter of fundamental fire behavior advancement. The reviewers were further confused by our interjection of a fifth tier, the context of combustion processes. Finally, the reviewers noted, and we agree, that the contextual tier of combustion process was not an effective taxonomy within which to classify our study questions. In response, we eliminated the combustion context, and now simply classify the study questions and proposals underneath the four problem analyses.

2. The problem analyses: The depth of the four problem analyses (PA) was perceived as uneven, poorly documented (in some cases) and one reviewer noted they were "sometimes peppered with…unjustified assertions." We agree. Each was authored by a separate principal investigator or team, with not enough time or resources available within the timeframe to bring them all up to the same, higher standard. We expect and plan to continuously improve this plan. The reviewers generally accepted the four problem areas as an organizational context, although one reviewer strongly disagreed with the concept of separating the problems of Combustion and Heat Transfer and Complex Fuelbeds. In that regard, the reviewer notes, "Taken together, your Combustion and Heat Transfer and Complex Fuelbeds encompass what I see as that critical 'core' of fire research." Another reviewer saw a redundancy in the two problem analyses 'Fire Behavior Transitions' and 'Fire Event Dynamics.' We do not, and we stand on our assertion that the two classes contribute to our ability to describe the processes and associated research required to address them.

One reviewer felt strongly that it was well past the time to focus some R&D on understanding Transitions and Dynamics, stating "It is absolutely unconscionable that we do NOT have a crown initiation model developed from a firm scientific basis today!"

Reviewers question the segregation of complex fuels from the fundamental research. While maintaining these as separate problem analyses, we have integrated both aspects into several of the studies during subsequent (after the reviewers got their draft) development of the 'final' study plans submitted in chapter IV of this plan.

3. The study questions: Similar to our uneven treatment of the problem analyses, reviewers found a large disparity in completeness and thoroughness of the study questions. We agree. They were prepared by a variety of individuals and teams, and were intended as "straw-proposals" from which the team could parse several cogent, feasible studies for this plan (any future emphasis will be on complete study plans, such as submitted in chapter IV of this plan, and not on further development of the straw study questions). A reviewer noted that several study questions were beyond the scope of a single study and/or lacked cogent hypotheses or researchable questions. The team took this advice when selecting (and also combining) study questions from the review draft to develop the final study plans. The reviewer most strongly anchored to the concept of fundamental (core) fire behavior research identified the same set of studies as the team for further development. The team was somewhat validated (and grateful) for this congruence. One reviewer, in comments relating to the study of 'Numerical Simulation of Deep Fuelbed Test Burns,' noted "Presumably, results from this study should provide insights to the (separate) study question dealing with fire spread thresholds and flame structure." The team agrees, hence our recommendation that this work be tasked to our partner at NIST, in collaboration with other Forest Service scientists. Most reviewers corroborated the team's

judgment that, while relevant to fire R&D, the study questions under Fire Event Dynamics were of secondary importance to the current "core" initiative. We include a description of the team's rationale and disposition of these 'secondary' studies in chapter III of the plan. Finally, one reviewer reiterated his admonition that the team "…not focus too sharply on operational considerations."

4. How well did we (the Team) meet the challenge?: all reviewers were impressed with the evidence of a "virtual" national coalition of fire R&D scientists working together. One reviewer suggests we extend this to include international collaboration. Of course, we will as appropriate and effective. There was general understanding and agreement with our rationale for focusing on "core," fundamental efforts. Several noted that some, if not many, of the study questions have "been around for some time." All agree this effort is long overdue, and should be expedited beyond the pace suggested by the team.

SPECIFIC COMMENTS AND RESPONSES

INTRODUCTION

p.5, par.1 Did you have stakeholder participation in development of the the plan?

> Response: We involved stakeholders in three ways; extensively as equal partners in the portfolio plan (strategy) and, before that, in the development of the logical model. Development of this plan was primarily a science process but we also indentified stakeholders as peer reveiwers.

p.5, par.2 While I agree a more physical approach is warrant, we need to be careful it not the only alternative, have you considered an over-arching study question of reviewing and evaluating alternative modelling approaches that will meet the Wildland Fire and Fuel Strategic Plan?

> Response: No, only as much as the problem analyses talked about them. We disussed various approaches in the problem analyes but we chose not invest through this plan in a question of reviewing and evaluating alternatives. We are really focusing on the neglected study of physical fire sciences. We acknowledge that whatever end user model is finally devloped, it will necessarily be a hybird model.

CHAPTER I. SUMMARY

p.9 par1 Have you considered a secondary level of an international virtual fire science consortium: Canada, European Union, Australia, etc?

> Response: Yes, we have, particularly in the Core Fire Science Caucus. Although we have proposed an international virtual fire science consortium and set a goal to reach that, we haven't yet achieved it. We think that is most appropriatly done as part of the Core Fire Science Caucus. This advancement plan is really about managing our federal resources.

The Core Fire Science Portfolio Team, in particular, is the management organ of the virtual national lab. We know we are not the only laboratory; we are all in favor of finding ways to create a larger entity. This science advancement plan is to a way to manage U.S. investments in fire science and to collaborate among national resources. We realize that the bulk of research capacity and funding now resides outside the U.S., and we want to encourage any way that we can form a larger partnership.

Figure 1:

Comment: The existing 5 portfolios in the diagram appear to be silo and the Core Fire Science needs to be fundamental to the other four. Better knowledge and understanding fire in a diverse range of environments and landscapes will be main driver of the other portfolios. Have you consider some cross-cutting research themes across the fire SPA?

Response: That's what the Fire Strategic Program Area is responsible for. They are the integrator of all those themes, not the Core Fire Science Portfolio Team.

Figure 2:

Comment: Integrated FFM and CFS are cross-cutting themes.

Response: Yes, they are..

Comment: First three boxes are NOT discrete. They interact. Too simplistic.

Response: That is why we show them in the fashion we did, along a continuum. However, the structure of the portfolios is defined by the Fire and Fuels Strategic Plan, not by the Core Fire Science Portfolio Team.

Physical Fire Processes

p.12 See my comment on modeling approaches- I am concerned that the physics-based model (white box) will be completely operational and you should consider a hybrid modeling (grey box) approach- knowledge-based, theory influenced empirical models?)

Response: We disussed various approaches in the problem analyes but chose not invest through this plan in a question of reviewing and evaluating alternatives. We are really focusing on the neglected study of physical fire sciences. We acknowledge that whatever end user model is finally devloped, it will necessarily be a hybird model.

Combustion & Heat Transfer

p. 12 Topography?

Response: Topography is outside of the context of this part of the plan. Topography does not abosrb heat.

p. 13 It seems you would also have to consider (a) Complex Weather and Atmospheric Interactions AND Complex Topographic Influences. Why limit this “core” to only complex fuelbeds?

Response: We readily acknowledge that we have neglected complex topographic influences except with a discussion of it in the Fire Event Scale Dynamics problem analysis. It is addressed in several study questions as well. It is not addressed in this paragraph because we’re talking about heat transfer.

Fire Behavior Transitions

p. 14 Scaling of fires- smoldering fires (large woody material, duff), fuel dominant fires (low intensity- surface fires- low flames), wind dominant fires- increasing fuel stratum affecting fire behavior and wind field in different canopies, plume driven fires- interaction between fire-atmosphere and convection column (plume).

Response: Some of this we addressed in the Fire Event Dynamics and the Fire Behavior Transitions problem analyses.

p. 14 Consider the transition of spotting, spot fire propagation, and fire coalesce of multiple fires.

Response: see above.

Fire Emissions

p. 15 Where did this come from? Someone snuck a 5th Element in here (referring to a 5th problem). I’m not sure this is “core” fire. It deals largely in the social aspects. I understand you have to have the physics but it seems to have a secondary objetive to other 4 elements presented.

Response: The 5th element is listed here to be complete and true to the Fire andd Fuels Strategic Plan. It is addressed on the previous page before Combustion and Heat Transfer. Also the in the 3rd complete paragraph on page 10.

CHAPTER II—PROBLEM ANALYSES

Combustion and Heat Transfer Problem Analysis

Approach; Combustion Limits...

p. 18 There are mixes of live and dead. Could you think of this as a continum from all dead to all live rather than as two catagories?

> <u>Response</u>: In this plan we intend to deliberately address combusition-moisture relationships for live and dead seperately. If we learn that we can create a conitumum after this work, we will. We don't want to average the inputs, however.

Approach; Live fuel Moisture...

p. 19 There are mixes of live and dead. Could you think of this as a continum from all dead to all live rather than as two catagories?

> <u>Response</u>: In this plan we intend to deliberately address combusition-moisture relationships for live and dead seperately. If we learn that we can create a conitumum after this work, we will. We don't want to average the inputs, however.

Fundamental Departure in Theory and Approach

p. 20 Comprehensive testing of model should be proposed for model acceptance and adoption.

> <u>Response</u>: This is not about the application of models; it is about developing the fundamental theory that go into making the models. We are breaking it down into physical processes; we want to validate **components** of the model that relate to specific physical processes and validate with live data.

p. 20 Consider a proposed three-tiered structure for calibration and verification: (1) laboratory experiments, (2) field experiments and (3) well-documented wildfire data (scaling up validation procedures). There could be existing data set available (Canada and Australian fire behavior data set) to assist in the validation of the next generation fire.

> <u>Response</u>: This is not about the application of models; it is about developing the fundamental theory that go into making the models. We are breaking it down into physical processes; we want to validate **components** of the model that relate to specific physical processes and validate with live data.

p. 20 These 3 (Separation.. Time, and Discrete) are all the same, a function of the fuelbed.

> <u>Response</u>: They are 3 completely different heat transfer processes. We make a mistake of trying to make general equations when there are three processes.

Complex Fuelbeds Problem Analysis

Problem Description

p. 23 Part of the research program is to determine what fuel parameters that are driving the fire spread- behavior and different scales or transitions of fire. Example- smoldering- large woody material, duff, surface fire -low intensity fire under light wind conditions- fuel load fuel continuity could be the drive fuel parameter, under stronger- suspend and shrub fuels may be important, crowning- ladder and canopy fuel, spotting- bark, ladder fuel and plume dynamics, etc

> Response: We have noted, and modified the problem statement.

Approach to Problem Solution

p. 25 Diural and overnight fuel moisture should be included, up to four-day forecast fuel moisture modeling- improve planning of prescribed fires and suppression resourcing.

> Response: We are talking about the fuel moisture's initial state variable. We are not trying to prove diurlal or longer period fuel moisture transfer with the atmosphere. We are dealing with those as precursors and considering moisture content as an initial state variable.

Characterizing spatial and qualitative complexity of fuels

p. 26 Fuel characterization must link to fire behavior model. The fuel complex theme needs to link with the combustion heat transfer and fire behavior transitions. In my experience it is very difficult to conduct an independent fuel program for fire management without fire behavior. Example, in are Bushfire CRC we original have a fuel project independent from the fire behavior project. Combining the two projects: Fuel and fire behavior modeling. Therefore in your detail research plans I recommend you show a strong linkage, cross-cutting research activities between fire behavior scientists and fuel modelers.

> Response: We agree, and we are showing these linkages in the detailed research plans.

Dwellings and structure fuelbed components

p. 28 While dwelling structure is important, you need to consider firebrand (embers) attack on dwelling. The work in Australia as shown the major source of house ignition from wildland fire is firebrand (embers). Thus, spotting and spot fire behavior (back fuels and other ember source) should be critical component of this study.

> Response: Good point. We don't think about embers enough, especially embers and structure. Our collaborators, with our support, are pursuing that. Our formal collaborators at NIST are directly addressing ember production and ignition possibility. See next paragraph.

Figure 4

p. 31 Recommend to add bark characteristic as a fuel stratum and in the sub-elements or the transition and event dynamics add spot fire behavior.

Response: That is a good point. Bark is indeed integral ot the FCCS system; it can be found in the ladder fuel catagory. There are very few speices in the U.S. where that is an issue.

Fire Behavior Transitions Problem Analysis

Problem Description

p. 33 (3a) transition from surface and/or crown fire starts spotting.

Response: "including fire brand generation" into that section.

Surface Fire to Crown Fire Transition

p. 35 Are you proposing a research program to collect data from various scales: laboratory experiments, field experiments and well document wildland fires for model validation?

Response: In some cases, yes we are. We refer the reviewer to proposal titled "A Spatially Explicit Fuel Model."

Transitions between Flaming, Smoldering, and Residual Smoldering Combustion

p.35 What about emission and smoke dispersions?

Response: Emissions and smoke disperions is not within the scope of this Core Fire Science Advancment Plan. We addressed it in element 5 (Emissions) but find it is part of the Ecological and Environmental Portfolio Team's responsibility (see page 10).

Surface fire to crown fire transition

p. 35 Consider the transition of surface /crown fires and spot fire behavior.

Response: We have considered this, and such a consideration can be found by the mention of ignition point transfer on page 37 under *Surface Fire to Crown Fire Transition*, section c.

Fire Event Dynamics and Fire-Atmosphere Interactions Problem Analysis

What do we need to do first and foremost?

p. 44 Field experiments are very important but they can be very costly and time consuming. Also, could be limited on the range of conditions to conduct experiments. Should include a comment of opportunities to document wildfires (including instrumentations and fuel assessment for data collection).

Response: This is why you'll see strong linkages with the numerical modeling as surrogates for some of these field experiments.

CHAPTER III—STUDY QUESTIONS

p. 47 (the onion) See my notes on front cover about this diagram.

Response: We have addressed these commments in our Generalized Comments and Responses section of this appendix.

Workshop Participants

p. 50 There is a potential for some collaboration with European Forest Fire Researchers- some are collaborating with Rod Linn, Also, Mell has collaborated with the the Australian (Gould) on field experimental data for model evaluation.

Response: This is highly desirable.

Study Questions

Numerical Experiments for Assessment of Conditions Required for Crown Fire Propagation

p. 59 There is another compelling reason to figure this out – planning. Most of your orientation here in on the importance of the operational aspects. If we are ever going to be able to model a fire regime and ask society if it's acceptable we must answer this question. Of the same importance is given to initiation. You can't understand one without the other.

Response: Our orientation is on the physical; for both operational and planning. If this ends up operational, that will also work for planning.

p. 59 This is a very ambitious research question and a number of the following questions below will lead to a better understanding and application of numerical experiments. Current state of knowledge in numerical experiments the verification and criteria for verification of the numerical models are required. Questions one could ask to seek model evaluation:

1. Has the model been constructed of approved materials- i.e. best science, approved constituent hypotheses (in scientific terms)?
2. Does its behavior approximate well that observed in respect of real thing?

Does it work i.e. does it fulfill its designated task, or serve its intended purpose?

Response: We are not talking about producing a model here. We are looking at the heat balance combinations that sustain crown fires. We are not at the point of developing a predictive model, or conceiving a predictive model.

Characterizing Attributes of Combustion Critical Fuelbeds

Specific outcome

p. 62 You are proposing biological parameters for fuel moisture and flammability index. Consider a more physical process model for fuel moisture which could be applied in the numerical and physical models. If fuel and fuel moisture can be model by biophysical or bioclimatic regions then these model may be more transportable to other fuel types and the proposed next generation of fire behavior models.

Response: That is what we meant. We will delete the words “by species.”

Necessary Conditions for Crown Fire Initiation and Initial Spread

Study question

p. 68 Flame structure could be an important component of the surface fire behavior.

Response: A surface fire characteristic includes flame structure.

Hypotheses

p. 68 The relationship to mid-canopy wind to ambient wind in the open or a forecast wind (operational input in crown fire modelling).

Reponse: Part of what we are trying to do is look at the physics, the more complex fluid dynamics, in and below the canopy sturcture which can only be done currently thorugh numerical modeling. That is part of the reason for our focus on numerical modeling in the fluid dynamic aspects of crown fires. The simple relatinoships that we’ve so far developed for operational application are inadequate, and so we’re exploring the more fundamental physics.

Convective Plume Dynamics and their Impact on Fire Transitions

Study question

p. 75 Two forms to transition for scaling of fires (1) scaling up in size and intensity, and (2) fire growth and acceleration.

Response: we have added “including scaling in size and intensity, and fire growth and acceleration.” to the end of the paragraph.

Conditions Limiting Backing Fires

p. 80 Too specific [when uses additional words “in fine Surface Fuels].

Response: Thank you. We accept this comment and have deleted “In Fine Surface Fuels.”

The Plume Dynamics of High Intensity Fires

Title

p. 81 Initiation of spot fires (fuel/bark characteristics).

Response: Your point is well taken. We agree with the importance of spotting, but here we are talking about how the plume operations around high intensity fire. That is a different subject.

Study question

p. 81 Secondary to core fire science in my mind. Who cares about plume dynamics?

Response: This is addressed in general reconciliation responses above.

Airflow in the Vicinity of a Fire

Study question

p. 84 Again, secondary in importance or even tertiary.

Response: We agree; addressed in the general reconciliation section already.