Fire Science Strategy

Resource Conservation and Climate Change

September 2014

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ACRONYM LIST

CDC	Centers for Disease Control and Prevention
CO_2	carbon dioxide
DoD	Department of Defense
DOE	Department of Energy
ESTCP	Environmental Security Technology Certification Program
EPA	Environmental Protection Agency
GHG	greenhouse gas
JFSP	Joint Fire Science Program
LiDAR	Light Detection and Ranging
LANL	Los Alamos National Lab
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NIS	non-native invasive species
NIST	National Institute of Standards and Technology
$PM_{2.5}$	particulate matter 2.5 (particles less than 2.5 micrometers in diameter)
R&D	research and development
RxCADRE	Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment
SEMIP	Smoke and Emissions Model Intercomparison Project
SERDP	Strategic Environmental and Research Development Program
USFS	United States Forest Service
VOC	volatile organic compounds

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1.0 PURPOSE

The purpose of this Fire Science Strategy is to provide a framework for the Strategic Environmental Research and Development Program (SERDP) and its associated demonstration program, the Environmental Security Technology Certification Program (ESTCP), to advance solutions to current and future natural resource management challenges faced by the Department of Defense (DoD) and its military installations in regards to the use of fire. The background of fire science and associated outgrowths of management are presented as are the roles that various agencies and other organizations have played. The strategy SERDP/ESTCP proposes for the direction that fire science should take is presented from the perspective that current fire science is not capturing the fundamental core issues that support understanding fire behavior and enabling the development of ecosystem-based and air quality management models that rely on an understanding of such behavior. Although DoD must ensure that its unique management needs will direct its own science, the overall strategy that is being proposed for fire science will best be served by a coordinated approach with other agency leaders in the field.

2.0 BACKGROUND AND OVERVIEW

Fire plays a vital role in the ecology of fire-adapted ecosystems and, due mostly to the introduction of non-native invasive species (NIS), in non-fire-adapted ecosystems as well (in combination, fire-affected ecosystems [*sensu* USFS 2006]). The DoD manages both types of ecosystems. Fire occurrence on DoD lands also differs by vegetation type. Although the actual acreages have not been updated recently, a 1992 study commissioned by the United States (U.S.) Environmental Protection Agency (EPA 1992) estimated that DoD unimproved lands include about 5.2 million acres of forested ecosystems, almost 2.5 million acres of which are southern yellow pine (*Pinus* spp.; this currently includes over 0.6 million acres of managed longleaf pine [*P. palustris*], Robert Larimore, pers. comm.). Other significant non-forested vegetation types in which fire can be a management issue include about 7 million acres of the sagebrush (*Artemisia* spp) ecosystem, 10 million acres of desert [scrub], 4.3 million acres of savannas and semi-arid shrublands (oak, *Quercus* spp.; mesquite, *Prosopis* spp.), pinyon (*Pinus* spp.)-juniper (*Juniperus* spp.), and chaparral-type ecosystems, and 0.7 million acres of annual and perennial grasslands (EPA 1992). Because of pyrophytic NIS, mostly grasses, ecosystems such as sagebrush and desert scrub have been subjected to dramatic decreases in fire-return intervals. In particular for desert scrub ecosystems, however, many of the native species are intolerant of fire.

Mission Relevance of Fire: Fire is a fact of life on a military installation. Significant training time is lost due to wildfires, yet training (as well as testing) activities themselves are a significant ignition source. The military Services spend millions of dollars annually on claims, asset loss, and suppression activities due to wildfire. Depending on the conditions under which it occurs, fire also can contribute to air quality concerns. Finally, as mentioned above, fire is a key ecological process that needs to be considered both in the management of various ecosystem types and for mission support (i.e., maintaining safe and realistic training environments). The various competing constraints, benefits, adverse consequences, and costs associated with fire create a complex management challenge, especially as it relates to the appropriate role of prescribed fire and the priority that DoD should place on its use. A better understanding of fire behavior, its purposeful manipulation to achieve desired management objectives, and the consequences of wildfire versus prescribed fire for air quality, ecological effects, human health and safety, and mission support is needed to assist DoD managers not only in the proper use of fire but also in understanding the trade-offs involved in deciding to burn or not to burn. This strategy document aims to outline the research and demonstration investments needed to understand the mission relevance of fire and how that may affect its purposeful use and prioritization.

Fire as a Management Tool: Currently, prescribed fire is the primary tool by which DoD installations mitigate wildfire risk, manage fire-adapted ecosystems and their associated listed and at-risk species, and provide relevant training environments. DoD annually conducts more prescribed burning (about 600,000 acres total; Robert Larimore, pers. comm.) than any Federal agency other than the U.S. Forest Service (USFS), despite managing a fraction of USFS's acreage. Such burning primarily occurs in open-canopied forest ecosystems and primarily in the Southeast. In forest ecosystems in particular, use of prescribed fire is an integral part of the management toolbox associated with DoD's approach to ecological forestry (see Franklin et al. 2007 for a description of ecological forestry principles).

Fire is an extremely complex physical process. Although an aggressive fire research and development (R&D) effort has been ongoing for more than 50 years (USFS 2006), which has led to improved understanding of fire behavior and fire effects, important research gaps remain to be addressed relative to fire behavior and its consequences for the use of fire as a management tool and in particular for the types of ecosystems that DoD manages. In addition, the consequences of deciding not to burn are key data gaps as well, especially if prescribed fire is viewed from a risk management perspective in which the risks of burning are balanced against the risks of not burning.

Fire is one of the most effective ecological processes for restoring historically disturbed lands to functioning ecosystems that meet current and future military land-use and stewardship objectives. Under current conditions, the presence of insects, disease, and drought affect forest health and the degree to which fire can be applied as a management tool and its effectiveness. Under a future of climate change-related perturbations and expanding presence of NIS and native pests and diseases, understanding how fire affects recovery, restoration, maintenance, and resilience of ecosystems on which DoD depends will present new challenges. It is unclear if DoD (and the ecosystems it manages) is prepared for the consequences of these increased and unprecedented stressors on DoD lands and the new threats and requirements for sustainment they pose. Specifically, in regards to the development of a fire science strategy, it is critical to understand where and when fire can be a primary tool for meeting future management needs and how fire-adapted ecosystems will respond under a changing climate regime and novel stressors.

Ongoing and Emerging Research Needs: The use of fire for management purposes often is constrained by air quality and smoke safety (visibility) considerations. Wildfires tend to occur at times, such as the summer, when human populations are most susceptible to smoke exposure due to other concurrent air quality issues. These fires tend to consume heavier fuels (i.e., woody fuels and not just fine fuels) and organic soil horizons and can smolder for extended periods. The incomplete combustion associated with smoldering may lead to much higher emissions of reduced compounds, including many air toxics. Such fires also pose higher risks for human safety, assets, training, and unplanned suppression costs. Prescribed burning, on the other hand, is commonly performed with the aid of fire weather forecasting systems that can help to minimize direct human exposure to smoke, minimize the impact to transportation activities, and limit fire severity and smoldering combustion by constraining the temperature, humidity, wind, and fuel conditions under which burning occurs.

To support DoD's continued use of fire as a management tool, SERDP has funded efforts to address how best to characterize the emissions associated with fire and their dispersion in the atmosphere, as well as to understand how fire acts as a disturbance process that resets ecological communities. Emissions characterization focused mostly on regulated constituents, such as criteria pollutants, which have established exposure thresholds, and hazardous air pollutants, which do not have established exposure thresholds but instead are regulated on the basis of compliance with using the maximum available control technology. An important by-product of this work, however, was to provide information on the greenhouse gas (GHG) emissions profiles of fires. Further work on characterizing GHG emissions, along with other climate-forcing agents (e.g., soot carbon and brown carbon; *sensu* Andreae and Gelencsér 2006) generated by fire, and their relationship to fire frequency, intensity, and severity is needed to understand the trade-offs involved. The preceding types of data, along with other SERDP research on the carbon cycle of DoD forest ecosystems and the relationship to ecological forestry, are attempting to provide DoD resource managers the information and tools they need to manage their forests for multiple benefits, such as: military mission support, carbon management, smoke management, biological diversity, and other desired ecosystem services. Section 4.0 provides additional details on SERDP and ESTCP investments to date.

Continued collection of data and development of models are needed to characterize emissions resulting from prescribed burning and wildfires that occur on and adjacent to DoD lands and to accurately allocate the source contribution of these fires to regional air quality in comparison to other sources. Information is needed for the variety of fire-adapted ecological systems managed by DoD and via characterization protocols that are standardized, transferable, and accepted by the regulatory community. Such work also should contribute to: (1) information on the types and amounts of emissions that play a role in climate forcing and their fate and (2) our understanding of the differences in emission profiles between fire-maintained stands and fire-suppressed stands that may burn under unfavorable conditions as a wildfire. This information is vital in meeting air quality requirements while maintaining the ability of DoD resource managers to use fire as a management tool.

Agency Fire Science and SERDP/ESTCP's Niche: The need to understand both the role of wildland fire as an ecosystem process and the appropriate use of fire as a management tool has been recognized for years by DoD and other agencies. As part of the 1998 appropriation, Congress directed the Department of Interior and USFS to establish a Joint Fire Science Program (JFSP) to supplement existing fire research capabilities. The new program was designed to provide a scientific basis and rationale for implementing fuels management activities, with a focus on activities that would lead to development and application of tools for managers. National in scope, responsive to multiple agencies, and broad in its mandate, the JFSP is a critical partner in fire science funding. The JFSP provides targeted funding through its investment strategy and science plans focused on research needs identified by fire and fuels managers. Despite these successes, major challenges remain in which fundamental science questions—such as those related to fire behavior—need to be addressed first to pave the way for significant advancements related to management applications.

Although fire research has been dominated by the USFS, numerous other agencies and research organizations have invested in this area. Some of these entities include the National Aeronautics and Space Administration (NASA), EPA, National Center for Atmospheric Research (NCAR), National Institute of Standards and Technology (NIST), Los Alamos National Lab (LANL), Joseph W. Jones Ecological Research Center, and numerous universities, with each entity bringing new perspectives, tools, approaches, and insight to address fire science needs. Unfortunately, the realities of funding limitations rarely lead to comprehensive "big science" approaches or breakthroughs in fire science tools.

SERDP and ESTCP have supported research and demonstration/validation, respectively, to provide DoD managers the understanding and tools needed to manage fire safely and effectively to achieve desired ecological conditions while protecting assets and air quality and facilitating the military mission. This work has focused on DoD-relevant vegetation types and associated needs, which often have been underrepresented in the work of other fire science efforts. Fire will remain an important ecological process that will require human intervention to either initiate or prevent, as appropriate, and to manage its consequences under a changing climate and other stressors. Given this assumption, SERDP and ESTCP have a need to assess their current contributions to fire science research and demonstration against the backdrop of emerging needs and science gaps and to determine, in collaboration with others in the fire science arena, its appropriate niche to guide future investments and partnering opportunities. This strategy document is intended to serve that purpose and will be guided by a conceptual model introduced in the following section.

3.0 A GUIDING CONCEPTUAL MODEL

Although considerable overlap among all agencies' fire science needs exists, the current focus of fire research has not sufficiently addressed in scope or pace the needs of DoD. The uniqueness of DoD lands and land management objectives, in particular, have resulted in knowledge gaps in meeting fire science requirements. These objectives include a focus on prescribed fire versus suppression, sustaining the military mission through fire management, indirect suppression tactics, and sustaining particular ecosystems, specifically the recovery and maintenance of the longleaf pine ecosystem in the southeastern U.S. for which DoD is a significant land manager. Perhaps in common with other agencies, however, fulfilling the science needs associated with these objectives also requires an understanding of the risks and trade-offs involved with not using fire as a management tool and how these change over different time horizons.

In addition, new regulatory environments should be anticipated as current compliance constraints will not likely remain static. For example, although a mandate for carbon management, especially sequestration, does not currently exist, land management agencies certainly should prepare for that eventuality. These types of data, along with research on the carbon cycle of DoD forest ecosystems and the relationship to ecological forestry, would provide DoD and other fire and resource managers the information and tools they need to manage their forests for multiple land management and ecosystem services benefits. Finally, climate change and other issues of non-stationarity related to land use and NIS will present new challenges.

SERDP's initial focus on fire-related science was driven in part by the outcomes of a workshop conducted in February 2008 (HydroGeoLogic 2008). With respect to fire science, the workshop identified three priority areas for SERDP's future research investment that can be summarized as follows:

1. Improve characterization, monitoring, modeling, and mapping of fuels to support enhanced smoke management and fire planning at DoD installations.
2. Enhance smoke management at DoD installations using advanced monitoring and modeling approaches.
3. Quantify, model, and monitor post-fire effects at DoD installations to improve fire management effectiveness.

Although SERDP used the preceding to direct its fire science investment to the present day, it also became apparent during the execution of the research that an overall conceptual framework was needed to direct future research and demonstration investments, especially as the role of fire behavior was not previously addressed explicitly and the new challenges described above arose. To address this oversight, this strategy document first develops a conceptual model as a basis for identifying future priority research and demonstration investments relevant to DoD ecosystem, air quality, and carbon management needs.

Conceptually, fire science is a fully integrated, interdisciplinary area of inquiry that leads to many cross-cutting themes and practical problems for R&D. Efforts to comprehensively address fire science inevitably become cumbersome or too simplistic. For the purpose of this document, we rely on a simple conceptual model for guiding future SERDP/ESTCP-funded research and demonstration investments in fire science. The conceptual model is not meant to represent the entire universe of fire science; rather, it helps to emphasize and bound the R&D niche applicable to SERDP and ESTCP and their missions to address DoD-relevant environmental management needs and responsibilities. Some of these needs and responsibilities may overlap with those of other agencies and thus form the basis for possible collaborative relationships. For example, Sommers et al. (2014) provide a framework (their Figure 1) for organizing research needs associated with wildland fire emissions, carbon, and climate that overlap with some of the components of the conceptual model described below.

The conceptual model (see Figure 1) includes five core areas (blue boxes) of research/ demonstration that are needed to support DoD management needs and responsibilities. These are: (1) fire behavior, (2) ecological effects of fire, (3) carbon accounting, (4) emissions characterization, and (5) fire plume dispersion. The last four core areas represent end points of potential management or regulatory concern to DoD. Fire may have other consequences for DoD, such as impacts to built infrastructure and training/testing missions. These end points are not addressed as separate research areas, but are considered in the context of ecological effects as other constraints.

As indicted by the linkages (green lines), fire behavior is an important condition for understanding the implications to DoD of the other four core areas and so becomes a fifth area of R&D focus. For purposes of this document, fire behavior is defined as the manner in which fuel ignites, flame develops, and fire spreads as determined by the interaction of fuels, weather, and topography. It can include a consideration of multiple ignition sources—the types of which and their spatial patterns of ignition can differ—and their interactions. Emissions production, although tightly linked to the combustion process, is considered separately and from the characterization standpoint, whereas fire plume development and rise phenomena are considered part of fire plume dispersion. Others may define what is meant by fire behavior somewhat differently; the manner in which it is defined in this document is to ensure that the focus for SERDP/ESTCP investment is on better addressing DoD management and compliance needs versus better understanding fire behavior per se.

The red boxes—vegetation/fuels, topography, and current meteorology/climatic change—depict enabling conditions that influence not only fire behavior but in some cases other core areas in a direct manner as well. These influences are depicted by the purple lines. The model also adds an element of dynamic change in that future climates may be different than current climates, which may lead to changes in vegetation/fuels. In addition, long-term changes in enabling conditions may lead to alterations in fire regimes with subsequent feedbacks to the vegetation/fuels. Finally, the green box highlights fuel consumption and (1) its tight linkage to fire behavior as a direct outcome of a fire and (2) its direct influence on the other four core areas. Although other outcomes of fire behavior certainly can be identified, fuel consumption is a critical aspect of a fire to quantify.

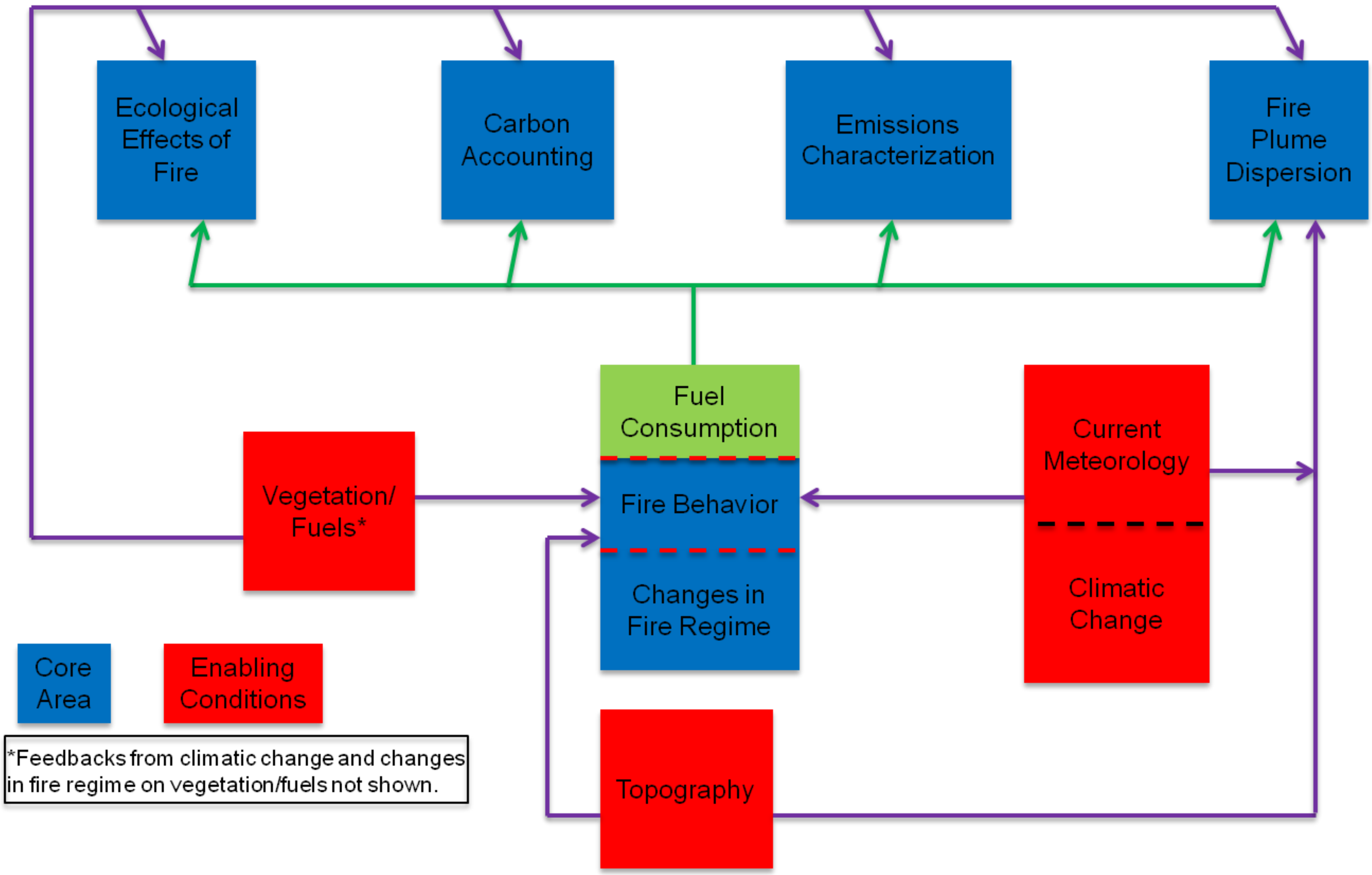

Figure 1. Conceptual Model for Guiding SERDP/ESTCP-Funded Research and Demonstration Investments in Fire Science

4.0 CORE AREAS OF RESEARCH AND DEMONSTRATION

In this section the five core areas are further discussed with respect to desired outcomes of SERDP/ESTCP investments, state of the science, SERDP/ESTCP investments to date, and cross-cutting themes. In some cases advancement of the science within a core area also will be dependent on advancing our understanding of the role of enabling conditions and their interactions in particular with fire behavior.

4.1 FIRE BEHAVIOR

Fire behavior is a core fire science topic area that serves as the foundation of future investments in improved understanding of ecosystem response to fire (ecological effects), fire plume (smoke) dispersion, fire emissions related to both flaming and smoldering conditions, and carbon accounting as related to the life cycle of fire-adapted ecosystems. Fire behavior is dependent on interactions of fuels, weather, and topography and improved understanding of these interactions, as well as fuel consumption outcomes (Ottmar 2014), is critical for advancing modeling and understanding of fire behavior and ultimately its effects.

Desired Outcomes*:* To develop, demonstrate, validate as appropriate, and transition the science needed by DoD fire and resource managers to understand and apply fire behavior as a management tool for those ecosystems of management concern to DoD. In particular, given the prevalence of the use of prescribed fire by DoD managers to mimic low intensity surface fires, a desired outcome is improved understanding of the processes involved in fine fuel heat exchange, ignition, and fire spread and how they may be affected by fuel condition, incorporation of this understanding into fire behavior models, and subsequent validation of those models. Understanding, models, and tools will be appropriately targeted to the end user, whether this is an installation-level manager, military Service regional support center, or contracted support.

State of the Science: Fire behavior remains an elusive area of inquiry with few studies that comprehensively define basic heat transfer processes (e.g., radiant or convective heat release and consumption) and few tools capable of integrating and advancing science in the other dependent core areas. Predictive modeling tools that describe the pyrolysis and combustion processes have been dominated by empirical and semi-empirical approaches, whose integration into the other core research areas that depend on first understanding fire behavior has been problematic. Finney et al. (2013) have suggested that to drive future advancements in fire behavior model development what is first needed is a common formulation or theory of wildland fire spread that is physically based and not just empirical. They identify four potential areas of inquiry: (1) fuel particle exchange; (2) role of convection; (3) definition of, and criteria for, ignition; and (4) burning of live fuels (as distinct from dead fuels).

Modeling of fire behavior has recently been advanced by the development of coupled fire-atmospheric numerical models that capture the fluid dynamics of the fire environment, but a lack of comprehensive datasets still limit real-world validation of such models. The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) effort represents the most significant investment in this area to date. Convective heat transfer is now recognized as playing a critical role in fire spread yet validating estimates of it is hampered by the inability to measure convection in the field. In addition, the physical processes associated with the burning of fine fuels and the resultant effects on fire spread require additional attention (Finney et al. 2013). Results from such research need to be incorporated into the next generation of fire behavior models.

Vegetation/fuel characteristics, topography, and weather are key enabling conditions that affect fire behavior. Vegetation/fuel characterization (see Weise and Wright 2014 for a recent summary of the issues involved) is also a vital need affecting our understanding of the other four core research areas. Some overlap of required fuels information likely exists across the five core areas; however, each area also has its own unique information requirements. Research in this area should recognize these different needs. Although DoD's needs regarding fuel and vegetation mapping are not unique (see Keane 2013), neither are they being entirely met. Unmet needs for vegetation/fuel bed information for the dominant fire ecotypes and purposes represented on DoD lands remain a critical data gap. These include the concentrations of DoD lands in the Southeast and arid and semi-arid Southwest that are represented by system types of open canopy pine/oak stands with surface fire regimes, grasslands, and shrub types such as pocosin and chaparral. In addition, the presence of insects, disease, and long-term drought affect fuel conditions and as a result need to be considered as part of fuel characterization. Information and protocols are needed at the appropriate spatial scale to match the relevant management question, with sufficient comprehensiveness (all key vegetation/fuel/fuel moisture components), accuracy, repeatability, and ease of collection to meet all of the core area needs. Light Detection and Ranging (LiDAR) has represented a tremendous advancement in the science of fuel loading measurements and the ability to accurately measure topography, factors that both contribute to how a fire will behave, though its potential has yet to be fully realized.

Weather, however, remains the most dynamic driver of the combustion environment and fire behavior. Current weather prediction models produce coarse-scale ambient wind fields without sufficient turbulent structure to predict fire behavior or to incorporate fire-induced feedbacks to wind fields. Variability (i.e., turbulence) in wind fields are now known to be one of the dominant factors in influencing fire behavior; however, modeling wind fields at an appropriate scale remains computationally expensive and difficult to measure and validate comprehensively in the field.

As mentioned before, fuel consumption is an essential linkage between fire behavior and the other four core research areas. Accurate estimates of fuel consumed in a fire are necessary to fully understand its effects and consequences. Several fuel consumption models are available, but either lack adequate validation or do not adequately represent consumption of specific fuel bed categories such as deep organic layers (Ottmar 2014). Additional issues related to fuel consumption are addressed under the other core areas.

The fire-science related disciplines to date have paid too diffuse and limited attention to investing in model validation, with the result that today's models are not adequately validated prior to being released to practitioners (Alexander and Cruz 2012). In addition, although a number of fire behavior models are available that are supposed to provide managers predictive capabilities, no inter-model comparisons have been conducted to assess limitations, cost, and performance capabilities across fuel types represented on DoD lands. Models also need to be validated against multiple vegetation types and conditions (e.g., regularly burned versus fire suppressed). Finally, usability by the manager has not been evaluated. This a fundamental gap in DoD's fire management needs.

SERDP/ESTCP Investments to Date*:* Except in one instance, the focus for SERDP and ESTCP R&D has not been associated with fire behavior directly. Completed SERDP research projects associated with emissions characterization used several different approaches to measure fuel loadings, as well as fuel consumption, but they did not explicitly evaluate specific fuel measurement approaches and determine their relative strengths and weaknesses for emissions characterization, let alone for fire behavior modeling needs. In addition, various weather models have been evaluated and modified to better understand fire plume behavior and to drive dispersion models but again such models were not explicitly evaluated in the context of fire behavior modeling (Odman 2012). To begin to move DoD in a direction of focused fire behavior R&D, an ESTCP project (Furman 2013) was initiated in FY13 that is demonstrating and validating the LANL FIRETEC wildfire behavior model in a longleaf pine ecosystem for the purpose of deriving management recommendations. This is the most explicit example to date of SERDP/ESTCP investment in fire behavior science and leverages RxCADRE data funded by the JFSP.

Cross-Cutting Themes*:* The four other core research areas (ecological effects of fire, carbon accounting, emissions characterization, and fire plume dispersion) are each dependent upon the advancement of fire behavior science. Each area will dictate its own requirements as to the scale and resolution needed from fire behavior modeling and prediction such that the data requirements for each core area may differ.

4.2 Ecological Effects of Fire

The challenge of managing fire effects on ecosystems and biodiversity under current and future climate regimes is a top strategic priority for DoD. Within this focal area, questions remain about the effects of fire on short term listed and at-risk species management, long-term ecosystem responses to climate non-stationarity, and the management of biodiversity under the current climate and plausible future climate change scenarios.

Desired Outcomes*:* To develop, demonstrate, validate as appropriate, and transition the science needed by DoD fire and resource managers to understand and apply the effects of fire—as well as to understand the consequences of inadequate fire frequency in fire-adapted ecosystems—on ecosystems, species, and biodiversity with an emphasis on those ecosystems and species of primary management concern to DoD. Understanding, models, and tools will be appropriately targeted to the end user, whether this is an installation-level manager, military Service regional support center, or contracted support.

State of the Science*:* In general, the translation of research to management in regards to fire effects has largely been realized in the realm of listed and at-risk species management and the recovery of the dominant tree species within an ecosystem. A recent review not only provided a blueprint for fire effects research needs, but also underscored the need for linking the research enterprise to the development of tools that directly address related decision-support needs for fuel and fire management (Hyde et al. 2013). Understanding ecosystem resilience under non-stationarity, particularly within the context of fire behavior and potential alterations in fire regimes, is a long-term strategic research challenge. This topic is increasingly found in the literature, but often only addressed as a theoretical exercise.

DoD has a need to understand those factors that govern resilience of fire-affected ecosystems to sustain a suite of habitat types on which its agency missions depend. Furthermore, DoD’s need for understanding also extends to the intersection of fire and fire interdependent systems and the ability to sustain mission capabilities without degradation. In particular, synthesizing the implications of the numerous studies, demonstrations, and research projects associated with longleaf pine restoration and management—an ecosystem of critical interest to DoD—is a pressing need. What remains to be determined are: (1) the underlying mechanistic controls of managed fire regimes on the recovery, restoration, and maintenance of fire-adapted ecosystems and their biodiversity across ecosystems and species of interest to DoD, as well as the unwanted impacts of wildfire on non-fire adapted ecosystems due to the presence of NIS; (2) an understanding of the critical ecosystem function of nutrient cycling under non-stationary conditions in the context of fire management; (3) an understanding of community assembly, disassembly, and novel reassembly in a fire-managed, no-analogue future; and (4) the relationship of fuel hazard reduction techniques to protect built infrastructure and training/testing missions to their ecological effects. To address the preceding, research will need to address different levels of effects, in particular first and second order effects (Hyde et al. 2013).

SERDP/ESTCP Investments to Date: Current SERDP investments have taken a regional approach. A primary focus has been on the southeastern U.S. and the longleaf pine ecosystem and understanding the effects of fire on geochemical processing and soil ecology, listed species habitat—in particular the red-cockaded woodpecker (*Picoides borealis*)—and overall biodiversity, and ecosystem recovery and maintenance. Other ongoing research investments include: (1) understanding the role of fire in restoring and maintaining dry tropical forest on Pacific Islands and the role of NIS in these systems in promoting fire; (2) the interaction of fire, vegetation, hydrology, and climate change on permafrost dynamics in interior Alaska; and (3) the interaction of fire, NIS, and climate change on vegetation dynamics in the desert Southwest.

Cross-Cutting Themes: Understanding the ecological effects of fire will involve making the necessary connections to fuel characterization, fire behavior, fuel consumption, carbon cycling, and even smoke production. Fire effects on biodiversity will be an important nexus for strategic ecosystem and disturbance regime focused science. Process-based models that connect carbon cycling, nutrients, and disturbance regimes will inherently integrate across these priority themes. Ultimately, understanding these interrelationships from the integrated themes will inform the trade-offs involved in ecosystem-based management in an uncertain future.

4.3 CARBON ACCOUNTING

The dynamics of carbon cycling in terrestrial (as well as aquatic) ecosystems managed by DoD are a strategic research priority. Understanding the carbon cycle in managed ecosystems is not only important to better manage these ecosystems, but will take on new importance in a carbon-strained world in which land managers will be expected to account for carbon sources and sinks and how their management affects their status. As a result, associated ecosystem-level research must consider the dynamics of the carbon cycle per se and how that cycle relates to carbon sequestration goals and the trade-offs involved with other ecosystem services (including supporting the military mission). The research also must incorporate the future uncertainty of climate change on processes that drive the carbon cycle. In particular for DoD, understanding how managed disturbances such as fire—with an emphasis on using the principles of ecological forestry and prescribed fire—affect carbon cycle dynamics is a priority.

Desired Outcomes*:* To develop, demonstrate, validate as appropriate, and transition the science needed by DoD fire and resource managers to apply knowledge of the carbon cycle in managed ecosystems, in particular fire-adapted ecosystems, to achieve carbon sequestration goals and other desired ecosystem services. Understanding, models, and tools will be appropriately targeted to the end user, whether this is an installation-level manager, military Service regional support center, or contracted support.

State of the Science*:* Carbon cycling in fire-adapted ecosystems, and its relationship to carbon sequestration goals, has until recently been largely viewed through the lens of event-driven emissions rather than an entire cycle to be managed over long time periods. Recent efforts have begun to place fire disturbance and associated emissions in a context of fire regimes that sequester carbon in years between events with recent studies highlighting the efficacy of frequent low-intensity fire for maintaining carbon stores (Hurteau and Brooks 2011) and facilitating recalcitrant carbon (e.g., charcoal) sequestration (DeLuca and Aplet 2008). Basic carbon accounting requires an assessment of both below and above ground carbon stocks. Although such assessments have been accomplished for a variety of ecosystems, especially for some common forest types that generally involve more commercially recognized species, it has not been accomplished for many of the ecosystems and associated species that DoD is managing with prescribed fire today or may need to plan for their management in the future (though see ***SERDP/ESTCP Investments to Date*** below). Additional strategic priorities include understanding the (1) tradeoffs involved in prescribed fire versus wildfire regimes for carbon management (see Section 4.4 for issues associated with fire emissions in general), (2) future carbon carrying capacity under climate change for ecosystems such as longleaf pine that in many instances are still on a recovery trajectory from earlier silvicultural practices that deemphasized this ecosystem and its dominant canopy species, (3) processes involved in belowground carbon storage, and (4) rates and fates of recalcitrant carbon produced by fire.

Simulation models can be helpful for studying the relationships between fire, climate, vegetation, and carbon. Keane et al. (2004) identified over 40 fire-vegetation coupled models—or landscape fire succession models—that covered a wide range of ecosystems, geographic areas, and spatial scales. All models at a minimum linked fire and vegetation succession. Climatic processes often could be addressed as well in these models and to a lesser extent biogeochemical processes (Keane et al. 2004). With a focus on carbon accounting, those models that incorporate biogeochemical processing for different ecosystems as a way to understand carbon cycling, fire, and climate will need further attention. Nitrogen-driven models, however, have not been accurate at addressing the complexity of carbon dynamics in the southeastern U.S. Here, water-limited models have shown the most promise in capturing the carbon consequences of fire. With the advent of climate non-stationarity, simulation modeling tools will prove valuable in understanding future sensitivity to swings in climate variability that lead to forest changes and altered fire consequences, but these models must be evaluated (validated) in ecosystems and regions of DoD interest to accurately capture relevant dynamics. The lack of simulation models that incorporate realistic fire disturbance regimes and ecosystem response to both a current and non-stationary climate remains a research priority. To reflect realism models should be able to account for antecedent conditions and incorporate spatial and temporal variability in fire behavior and its effects.

Although a primary focus for DoD to date has been on open-canopied forests, a better understanding of carbon stocking in boreal forests, including soil carbon, and the consequences of altered boreal forest fire regimes and thawing permafrost could become an important future need as DoD manages extensive acres of training land in interior Alaska. Future research must more fully develop the understanding of the cyclical nature of fire disturbance and carbon source-sink dynamics in these ecosystems that are undergoing rapid change.

Emanating from the above needs and recent science are several opportunities to leverage demonstrations to help managers meet the challenges of carbon accounting and management. A carbon footprint tool—preferably one that is flexible with respect to data quality and transferable across ecosystems—is needed to estimate stocks and fluxes under different management trajectories. To accurately do so, existing process models (without a realistic fire-disturbance component) must be evaluated for their ability to capture carbon dynamics and whether they can serve as a foundation for developing process models that can incorporate fire behavior modeling of greater sophistication.

***SERDP/ESTCP Investments to Date**:* SERDP began investments in this area in FY11. Current investments represent the regionalized concerns of DoD. Four projects are ongoing and a fifth initiated research in FY14. A primary focus has been on understanding carbon stocking and dynamics, including in relationship to fire, in the longleaf pine ecosystem (for example, see Samuelson 2014); however, other open-canopied and fire-adapted ecosystems in the West and South-central U.S. that DoD manages are receiving attention. In addition, one project is addressing carbon management in novel ecosystems in Hawaii. Each project also is viewing its research on carbon accounting through the lens of ecological forestry and the trade-offs involved with managing for carbon and the effects on other ecosystem services.

***Cross-Cutting Themes**:* Understanding carbon cycling, carbon sequestration, and their dynamics will have natural cross-cutting relevance to the ecological effects core area above, with emphasis on the ecosystems and geographic areas of significant DoD management concern. Fire behavior and resulting ecological disturbance regimes and responses are additional critical ties. Long-term sequestration of carbon by fire in recalcitrant forms also may relate to investigations of the role carbon compounds (e.g., soot carbon, brown carbon *sensu* Andreae and Gelencsér 2006) play in air quality and climate forcing. Although better understanding the fire emissions characterization and sequestration aspects of carbon may be appropriate lines of research for SERDP to pursue, research focused on resolving the role atmospheric carbon plays in climate forcing falls outside of SERDP's fire research focus.

4.4 EMISSIONS CHARACTERIZATION

Air quality concerns resulting from wildland fires on DoD lands have become an increasingly complex issue with new regulations proposed for ozone and $PM_{2.5}$. Current concerns relate to those constituents of fire that are considered hazardous air pollutants; however, future requirements could extend to those constituents of fire that result in a climate forcing. The manner in which fire emissions have been characterized in the past has been highly variable making comparisons difficult. It is critical to account for and characterize the conditions that contribute to the uncertainties in estimating an emissions factor for each important constituent of fire—e.g., fuel loading, fuel consumption, fire severity, laboratory versus field measurements, ground versus airborne measurements, and smoldering versus flaming fire, secondary aerosol production, and so on—in a consistent and documented manner. Finally, although production of emissions is important, eventually the impacts of those emissions are the focus of management concern. Section 4.5 will address fire plume dispersion issues that must be improved to aid in the projection of emissions impacts.

Desired Outcomes*:* To develop, demonstrate, validate as appropriate, and transition the science needed by DoD fire, resource, and air quality managers to understand and apply information on the emissions resulting from fire, both prescribed fire and wildfire, for vegetation types managed by DoD to facilitate using fire as a management tool while meet air quality requirements. This includes not only refining specific emissions factors for air constituents of concern for DoD vegetation types under both flaming and smoldering conditions, but also includes improving estimates of fuel consumption to place those factors into context. Understanding, models, and tools will be appropriately targeted to the end user, whether this is an installation-level manager, military Service regional support center, or contracted support.

State of the Science: Emissions factors enable estimating the amount of regulated gaseous and aerosol constituents that are released during a fire. They are needed to address permitting requirements associated with meeting air quality requirements and if inaccurate and overly conservative could result in activity restrictions, such as the ability to conduct prescribed burns. For each gaseous and aerosol constitute the associated emissions factor will differ based on the vegetation type; fuel loading, geometry, moisture content; weather conditions at the time of the fire; and how efficiently the fuel is consumed. Measurement approaches—ground versus airborne, laboratory versus field, measurements during smoldering versus the flaming portion of a fire; as well as how pre-fire fuel loading and post-fire consumption were determined—also will affect the resultant calculation of an emissions factor.

Although emissions factors have been estimated for a number of years and for many vegetation types, the available information is quite variable with respect to the constituent measured, the measurement methodology used, and the conditions at the time of the fire. For supposed wildfires, current estimates for emission factors contained in EPA's *Compilation of Air Pollutant Emission Factors* (AP-42) are based solely on data generated in a laboratory setting. For prescribed burns, field data are generally more available than they are for wildfires but the quality of the data is variable for both methods and types of data collected. Moreover, the presumed dichotomy between wildfire versus prescribed burn emissions—given its focus on distinguishing purposeful versus natural or unintended ignition—may miss the point between distinguishing emissions that are of an air quality concern versus those that are not or are a necessary trade-off to meet resource management objectives, but in a manner that can be planned and controlled and the negative impacts minimized. This may require a new complementary way of classifying fires and their associated emissions factors along a continuum independent of their ignition source that instead considers fuel and weather conditions at the time of a fire and the resultant intensity and subsequent severity of the fire.

Particular methodological issues include the inconsistencies and inaccuracies that are present in how emissions factors are scaled to available fuel loads and post-fire consumption (see Section 8.1 in HydroGeoLogic [2008]). Although progress has been made (see ***SERDP/ESTCP Investments to Date*** below), reconciling laboratory results to field-based emissions estimates and ground-based to airborne-based estimates still remain a challenge. In addition, the preceding research requires reconciling the differences between smoldering and flaming combustion—which occur simultaneously during a fire but whose relative contributions to emissions differ in ways based on the type and severity of the fire that need to be quantified—and determining whether our generalized understanding of those processes are adequate. Finally, little is known as to how the heterogeneity of fuels and moisture affect emissions (mediated through fire behavior), yet theoretically these processes will be critical to combustion efficiency and the resultant emissions. In short, a better understanding of what constitutes the fuelbed at the time of a fire and how much of each fuelbed component is consumed via flaming or smoldering combustion will go a long ways towards supplying the proper spatial and temporal scaling factors for estimating the final amount of emissions by constituent generated by a fire. The final outcome of the preceding research—beyond the emissions factors and scaling estimates themselves—should be generally applicable, yet flexible, measurement and calculation protocols that enable some consistency and comparability of these estimates.

With the increased reliance on remote sensing approaches to measuring emissions factors, particularly from ground-based LiDAR or satellites for particulate matter, more attention is required to understand errors, fuel and fuel consumption estimates, and limitations of these approaches through demonstration and validation of new and emerging technologies.

SERDP/ESTCP Investments to Date: Two completed SERDP projects focused on developing emissions factors for prescribed burns for DoD-managed vegetation in the Southeast and Southwest (Johnson et al. 2014, Miller 2014). In combination these projects provided a unique comparison of laboratory and field emissions data for vegetation types in these regions (Yokelson et al. 2013). Additional comparisons of prescribed fire (in fire-maintained stands) versus simulated wildfire (high intensity prescribed burns in fire suppressed stands at Fort Jackson, SC) emissions and ground versus airborne measurements also were conducted. The campaign at Fort Jackson also involved a JFSP funded-research project and as such represented another leveraged opportunity. Finally, these projects did contribute information relative to characterizing greenhouse gas and particulate carbon emissions. Such information will become important for carbon accounting (see Section 4.3) and if certain constituents of fire that influence climate forcing come under increased regulatory focus.

Cross-Cutting Themes: Emissions factors are dependent on vegetation type and fuel loading and condition (e.g., moisture content), which affect emissions directly and indirectly through fire behavior. Current meteorology also affects emissions indirectly through fire behavior. In addition, the pattern of fuel consumption as dictated by fire behavior will reflect the relative contributions of flaming versus smoldering combustion and significantly determine the nature of emissions produced by a fire. As a result, a better understanding of fuel consumption will contribute to several core research areas. Finally, carbon emissions from fire must be integrated with carbon cycling research to understand fire as a cycle and not strictly an event for purposes of carbon accounting.

4.5 FIRE PLUME DISPERSION

Although related to emissions characterization in fundamental ways (e.g., aging of smoke plumes with dispersion and the secondary formation of aerosols), the core area of fire plume dispersion contains several unique sub-elements that are of critical research focus. These elements include fire plume development and rise phenomena, plume chemistry, local and regional day- and night-time smoke transport, super fog formation, and predicting and preventing visibility impairments from prescribed fires that potentially impact the military mission and public safety.

Desired Outcomes*:* To develop, demonstrate, validate as appropriate, and transition the science needed by DoD fire, resource, and air quality managers to understand and apply information on the dispersion of smoke resulting from fire. Outcomes will address both prescribed fire and wildfire for the vegetation types managed by DoD. The understanding and knowledge gained will be used to facilitate using fire as a management tool while meeting local and regional air quality and safety requirements. Understanding, models, and tools will be appropriately targeted to the end user, whether this is an installation-level manager, military Service regional support center, or contracted support.

State of the Science*:* Over the last 30 years, wildland fire plume dispersion research has largely concentrated on the public safety aspects of smoke management and dispersion and impacts to regional air quality. Current dispersion modeling lacks sophistication to provide practitioners with confidence to predict smoke or emissions impacts, largely due to poorly resolved and inaccurate wind fields. In particular, wind data need to better distinguish ambient wind fields from fire-induced wind fields in both the vertical and horizontal dimensions.

Goodrick et al. (2013) reviewed a number of the available smoke transport and dispersion models. They identified four basic model components typical of such models: (1) description of the emissions source (constituents and heat), (2) determination of plume rise, (3) movement of the plume/smoke (transport and dispersion) by the ambient wind, and (4) chemical transformation. They then described model types of different complexity that reflect a trade-off in more realistic physical descriptions of plumes versus increased computational costs. The review concluded with an overview of key areas of uncertainty that required additional research attention. These include improved: (1) understanding of the plume structure that results from the buoyant phase of plume development as it relates to the vertical distribution of plume constituents, (2) quantification of the number of cores contributing to an updraft plume for a given fire as a way to improve dispersal simulations, (3) linkage of smoke transport and dispersion models to fire behavior models to better capture the space-time variability of heat and emissions release rates across the landscape, (4) linkage of plume structures to prescribed fire ignition patterns, (5) fully resolved canopy sub-models within atmospheric models to improve dispersion predictions for low intensity fires to improve local smoke effect predictions, and (6) quantification of the advantages and limitations through validation of the various models and their components to assist managers with determining which model to use for which purpose (Goodrick et al. 2013). This last area of uncertainty can be addressed by efforts such as the Smoke and Emissions Model Intercomparison Project (SEMIP), which is funded by the JFSP. Given the widespread need of such an effort, including by DoD managers, this project could provide an opportunity for a leveraged effort with ESTCP, especially if it involves access to a common set of smoke modeling validation datasets.

Dispersion modeling is often not at a fine enough scale to account for the average prescribed burn, and the atmospheric feedbacks that govern the distribution of the burn emissions also are occurring at finer scale resolutions than typically considered. Current dispersion models are primarily designed to distribute smoke/emissions at a landscape or regional scale and have proven inadequate to predict smoke impacts in complex topography at a local or sub-regional scale. Visibility impacts have largely been the focus because of safety concerns; however, few night-time modeling tools exist and the dispersion dynamics of night-time smoke dispersion remain largely unstudied. In a related way, the development of super fog represents a rare yet potentially additive and catastrophic problem for prescribed burners in the Southeast. Considerable investment has occurred already in fire plume dispersion research and as a result—and as mentioned already above—future work should involve a focus on demonstrating and validating existing models.

We have learned that many compounds are created when biomass burns and then these compounds are subject to a complex series of secondary chemical reactions in the atmosphere. For example, volatile organic compounds (VOC) and are now viewed as potentially critical by-products of combustion that affect air quality. VOCs are precursors to ozone production, and research points to their role in downwind ozone formation as smoke ages. As a result, new areas of research must address how plume dispersion and atmospheric feedbacks with fire govern air quality impacts at multiple spatial scales. Until now, these processes have been allowed to interact only in simple ways or assumed to be too complex to accurately capture.

SERDP/ESTCP Investments to Date: Two completed SERDP projects focused on demonstrating and validating a fire plume dispersion model (Daysmoke), as well as advancing adaptive grid modeling and linkages to regional air quality models (Odman 2012, Unal and Odman 2004). RxCADRE burn data (data collection funded by the JFSP), including wind data, were used to validate the Daysmoke dispersion model as part of the Odman (2012) research project. This represents an advancement in the use of local wind information for model validation; however, this is an area that requires additional refinement and use of wind data. Miller (2014) conducted a limited comparison of the EPA Community Multiscale Air Quality modeling system with the BlueSky smoke modeling framework and concluded the latter may be more useful to local land managers in developing estimated smoke emissions from prescribed burns.

Cross-Cutting Themes: Fire plume dispersion has a direct relationship with fire behavior. For example, fire intensity, ignition pattern, and extent may determine the number of updraft cores, which will affect plume properties. Weather and topography will dramatically affect plume dispersion, as will vegetation when smoke stays close to the ground. The emissions produced by a fire provide the source material for not only dispersion but also for subsequent chemical and physical alteration as the plume ages.

5.0 SYNTHESIS

The following sections synthesize information from Section 4.0 to highlight the priority research and demonstration needs, as well as add new information regarding potential partnering opportunities. Sections 5.1 and 5.2 also are informed by the results of a special session on *State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues* that was held as part of the International Smoke Symposium in October 2013. Appendix A contains a summary of the conclusions and key research/demonstration gaps that emerged from that session. These priorities focus on what are suggested to be the appropriate niches for SERDP and ESTCP to fill in the fire science arena.

5.1 PRIORITY RESEARCH GAPS

For SERDP, research priorities always must be based on addressing science needs that are relevant to DoD's ability to meet its military mission and stewardship requirements. This means in part focusing on those ecosystems or vegetation types that are managed by DoD installations. In some cases, DoD can rely on the science of others; however, in situations in which it is a primary manager of a particular ecosystem—such as is the case with the longleaf pine ecosystem—DoD has an inherent responsibility to focus attention on particular ecosystems. As a result, a guiding principle throughout is to ***focus on fire-affected ecosystems/vegetation types of management relevance to DoD***. To the extent that general scientific findings will emerge, such a focus can still complement the research of others and contribute to an overall improvement in management-relevant fire science.

Emerging challenges, such as climate change and fire's role in contributing to both sources and sinks of carbon and GHGs, will require new understanding and tools. It is not SERDP's role to investigate how particular emissions contribute to climate forcings; however, given these emissions and their effects may become the focus of policy or even regulatory concern, it behooves DoD to understand how its use of fire may contribute to such emissions and associated management options. A second guiding principle, therefore, is to ***focus on those aspects of a fire-related issue that have a reasonable expectation of leading to a management action under DoD's area of responsibility and control***.

The continued use by DoD of fire as a management tool—given both its potential risks as well as benefits—is not necessarily a given. For prescribed fire to be viewed as a priority for land management, either for mission support or stewardship, its benefits must outweigh its risks. A third guiding principle, therefore, is to ***whenever possible identify the benefits of prescribed fire and the trade-offs associated with inadequate fire frequency that may increase the risk of wildfire, exposure to pathogens or disease, or loss of training realism***.

Fire Behavior: As discussed earlier, understanding fire behavior is foundational to improved understanding within the other four core areas of research. If SERDP is to play a role in conducting fundamental research related to the development/improvement of physics-based fire behavior models, that role should be focused on the types of fuel configurations and prescribed fire ignition patterns that DoD fire managers may encounter and for which an improved understanding of resulting fire behavior will improve desired management outcomes and enhance safety. SERDP also can contribute in ensuring that the vegetation/fuel characteristics that drive fire behavior models are appropriately characterized for DoD ecosystems and vegetation types. This will require coordination with the other fire science agencies to improve the characterization of fuels and post-fire consumption estimates in ways that can serve multiple uses yet improve the standardization, repeatability, and transferability across fuel types of methodological approaches. Although SERDP may not play a leading role in the initial development of predictive weather models, it can contribute to their needed enhancements and subsequent testing to support fire behavior modeling. Validation of fire behavior models is addressed in Section 5.2.

Ecological Effects of Fire: Use of fire to date in a management context has been largely focused on listed species habitat management or recovery and maintenance of dominant canopy species. NIS are creating new challenges to management regarding the role of fire in invaded ecosystems, whether previously fire-adapted or not, and emerging interest in biodiversity in general, ecosystem-based management, including applying the principles of ecological forestry, ecosystem services, the effects of a non-stationary climate, and novel ecosystems also drives the need to better understand the ecological effects of fire. The preceding suggests a shift in research focus from understanding fire as an agent of monotonic directional change to a dynamic process that creates a diversity of outcomes at multiple spatial and temporal scales. A better understanding of fire behavior in a mechanistic sense will be a key contributor to an improved ability to use fire to meet these new challenges and needs. This will require the coupling of fire behavior models with ecological effects process models. SERDP can play a role in the development and testing of these coupled models (with potentially subsequent validation through ESTCP) to meet the management, stewardship, and sustainability needs outlined above for ecosystems of concern to DoD. This research needs to prepare DoD for the potential of a non-stationary and, in some case, no-analogue future in which fire likely will still play a vital role in achieving military mission and stewardship objectives. In addition, effects research, while focusing on ecological effects, also should account for minimizing any adverse consequences to safety, human health, and military training/testing activities.

Carbon Accounting: Carbon accounting and management is likely to take on more importance for “land management” agencies over time as the nation seeks opportunities to use its public lands for carbon sequestration purposes. The types of ecosystems that DoD manages have not necessarily been the focus of research in this area and the nature of the fire cycle in fire-managed ecosystems creates additional complexities. SERDP (and ESTCP) have begun work in this area, mostly related to the types of open-canopied forest ecosystems that DoD primarily manages. Other ecosystems, such as the boreal forest in interior Alaska, may require attention in the future. Below-ground processes related to the carbon cycle, the effects on other ecosystem services of carbon management, and the role of fire as a cyclical process affecting carbon stocks all deserve additional attention, though these are all active areas of investigation under SERDP (and ESTCP).

Emissions Characterization: Much information exists on emissions characterization, including for vegetation types managed by DoD; however, approaches to characterization differ markedly making comparisons difficult. Improvements in and standardization of methods for measuring fuel types and loads and estimating post-fire consumption will be a key contribution (as described above) but is not sufficient. Although progress has been made, reconciling laboratory and field-based measurements, ground versus airborne measurements, and flaming versus smoldering emission measurements, and their use in estimating emissions from a fire remain a pressing concern, including how emissions scale with fuel loads and fire intensity and severity. In this regard, the current paradigm of prescribed fire versus wildfire may need to be revisited. SERDP (and ESTCP) can play a role in the development and testing (and validation) of standard practices; however, this may best be accomplished in collaboration with the science and regulatory agencies. Again, SERDP would need to focus on ecosystems and vegetation of management relevance to DoD.

Fire Plume Dispersion: Plume dispersion is important from both a local smoke management context to concerns with regional air quality. Similar to the discussion on predictive weather models above, SERDP at this time will not play a leading role in the initial development of fire plume/smoke dispersion, regional air quality models, and their coupling. Similarly, resolving how atmospheric chemical reactions further modify plume constituents currently is outside SERDP's area of responsibility. SERDP can contribute, however, to needed enhancements in the dispersion models, including addressing issues of plume structure and dynamics of updraft cores in relationship to fire behavior, night-time dispersion, complex terrain effects on smoke transport, and subsequent testing (and validation through ESTCP) to support smoke and air quality management needs, again with a focus on modeling the plume dynamics associated with ecosystems and vegetation of management relevance to DoD.

5.2 PRIORITY DEMONSTRATION NEEDS

Within the fire-science related disciplines to date, limited and too diffuse attention has been paid to investing in model validation, with the tendency for models to not be adequately validated prior to being made available to practitioners (Alexander and Cruz 2012). ESTCP provides a complementary program to R&D for the demonstration and validation of new technologies and methodologies. ESTCP can be used to leverage existing investments in fire-related models and decision support tools to further understand and show the applications and limitations of these models and tools. Fire behavior, fuel consumption, fire effects, and fire plume dispersion models (and their coupling) are of particular relevancy. Decision support tools, such as carbon accounting or footprint tools tailored to DoD ecosystems and vegetation types, also may need to be demonstrated and validated.

ESTCP demonstration projects primarily take place on DoD installations; as such, these installations can serve as outdoor laboratories and test beds wherein data collection for fire behavior and other model validation and testing can occur. RxCADRE, which has taken place at Eglin Air Force Base, is an example of this. To maximize the strategic value of ESTCP to the advancement of user-inspired fire science, one approach could be to pursue the use of model/tool inter-comparison projects to assess individual model and tool performance against quantitative field measurements and in the context of whether regional differences and otherwise significant environmental variation affect performance for intended uses. This may require separately funded efforts similar to the RxCADRE project to develop requisite data sets for comparison purposes when they don't otherwise exist. The JFSP's SEMIP might provide an opportunity for a joint effort at intercomparison.

5.3 PARTNERING OPPORTUNITIES

SERDP and ESTCP are not the primary funders of fire-related science in the United States. It is important that these programs partner with and leverage the efforts of those entities that have their primary missions directed to fire science. In this regard, the JFSP has the potential to be a valuable strategic partner in prioritizing, funding, and executing fire-related research. This program's 2010 Smoke Science Plan (Riebau and Fox 2010) contains a number of thematic areas whose objectives overlap with the research and demonstration needs identified in this document. It will be incumbent on the respective program managers, in consultation with their advisory bodies, to clearly define their program's research- and demonstration-related niches to maximize the complementarity of their funded efforts, leverage funding opportunities when possible, meet their primary customer needs, and avoid redundancies.

Because SERDP is a tri-agency program, the Department of Energy (DOE) and EPA also are key partners. The DOE is particularly interested in the carbon accounting issues and EPA is a key player with respect to emissions characterization protocol development and fire plume dispersion modeling.

The USFS, in coordination with JFSP or otherwise, will be an important partner in the core research/demonstration areas of fire behavior and the ecological effects of fire. USFS is also the key player in fuel mapping and consumption estimate protocol development and are active as well in emissions factor development, carbon accounting protocol development, and fire plume dispersion modeling. The U.S. Geological Survey is a key partner in furthering our understanding of the ecological effects of fire.

Downscaled weather models, high resolution wind forecasting, and remote sensing applications represent research and demonstration opportunities to engage new research partners, including NASA and the DOE National Labs, such as LANL. The DOE's Pacific Northwest National Laboratory was instrumental in advancing capabilities to detect and characterize gaseous emissions, as well as developing the associated spectral libraries, emanating from fires (Johnson 2014).

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APPENDIX A

INTERNATIONAL SMOKE SYMPOSIUM 2013 SESSION ON STATE OF FIRE BEHAVIOR MODELS AND THEIR APPLICATION TO ECOSYSTEM AND SMOKE MANAGEMENT ISSUES:

CONCLUSIONS—KEY RESEARCH/DEMONSTRATION GAPS

The following are key research and demonstration gaps extracted from the October 2013 International Smoke Symposium special session on ***State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues*** as synthesized by Prichard and Otmar (2014) that may be of relevance to SERDP/ESTCP or of interest to the Department of Defense:

Fuel characterization and consumption

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

Smoke and plume dispersion modeling

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

and modification. Variables to model and test include 1) fire growth and behavior, 2) fuel consumption, 3) influence of fuel moisture on combustion, 4) plume structure and transport, and 5) ground smoke impacts.

Fire behavior modeling

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

Fire-atmosphere interactions

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

Climatic change and ecosystem modeling

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

- Large, integrated science assessments are needed for climate change, regional assessments, and model validation and will require coordination to leverage funding to support them through shared funding and research projects.

Fire effects science

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

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

Photo: Blackmore, Andy. 2011. MCB Camp Lejeune Environmental Management Division. Camp Lejeune, NC.