Scientific Basis for Modeling Wildland Fire Management: The Phase II Report of the National Science and Analysis Team

EXECUTIVE SUMMARY

The National Science and Analysis Team (NSAT) was established to support the development and implementation of the Cohesive Strategy through the application of proven scientific processes and analysis. To achieve this goal, the NSAT is charged with three primary tasks:

1. Assemble credible scientific information, data, and preexisting models that can be used by all teams working on the Cohesive Strategy.
2. Develop a conceptual framework that describes the relative effectiveness of proposed actions and activities on managing risks associated with wildland fire.
3. Construct an analytical system using the products developed in Tasks 1 and 2 to quantitatively analyze regional and national alternatives identified by regional and national strategy committees.

Tasks 1 and 2 were addressed within Phase II, and will continue. Task 3 is exclusively a Phase III effort.

A wide range of individual scientists and analysts have participated in the NSAT, representing federal, state, and tribal agencies, universities, and various non-governmental organizations. During Phase II, the NSAT worked as a series of eight subteams, with each subteam assigned to a specific topical area. The topical areas were chosen not only to span the range of issues and processes involved in wildland fire, but also to take advantage of the special interests and knowledge of NSAT members. The eight topical areas are: 1) landscape resilience, 2) wildfire ignitions and prevention, 3) fuels management, 4) wildfire response, 5) fire adapted human communities, 6) firefighter safety, 7) smoke management, and 8) policy effectiveness.

Wildland fire is a complex phenomenon that encompasses numerous interacting social, ecological, and physical factors. The Cohesive Strategy can be viewed conceptually as a collection of management actions, policies, and activities, that collectively influence four major interacting processes: vegetation composition and structure, wildfire extent and intensity, response to wildfire, and community preparedness and resiliency. These processes in turn influence the goods and services received from forests and rangelands, firefighter and public safety, and homes and property affected by fire.

The NSAT subteam efforts built upon and expanded each of these major processes. For example, the wildfire ignitions subteam considered a broad range of factors that affect where, when, and how wildfires start and how various combinations of engineering, enforcement, and education can influence human-caused ignitions. Similarly, the fuels management subteam examined how various combinations of prescribed fire and other fuel treatments affect vegetation structure and composition, which in turn influence (and is influenced by) wildfire extent and intensity. Such interactions play out differently across different ecological biomes and at different spatial and temporal scales.

Due to the complexity of wildland fire, many of the identified factors necessarily overlap or intersect between and among topical areas. This is especially true for the more integrated issues such as landscape resilience, fire adapted human communities, and public acceptance and policy effectiveness. Thus the narratives provided by each subteam often reference components shared between teams.

In many ways the products from the subteam efforts reflect the state of knowledge about various aspects of wildland fire and the availability of existing models and data. Several trends are evident.

1. Fine-scale processes tend to be better understood than broad-scale processes or strategic issues. For example, there is an extensive literature on fire behavior and combustible properties of fuels; less is understood about the large-scale effectiveness of strategic fuel treatments.
2. There has been considerably more research focused on the biophysical aspects of wildland fire than has been directed at equally important socio-political issues. Thus we can assuredly state that fire-wise landscaping and construction materials will help reduce the incidence of homes lost to wildfire; we are less confident as to how to ensure such practices are implemented. Smoke is an archetypal issue—technically well-understood but socio-politically complex and difficult.
3. Integrated research efforts that focus on interactions among human and physical factors are becoming more common and are highly promising. For example, there is a growing body of research into how socioeconomic, educational, regulatory and enforcement factors relate to wildfire ignition processes.
4. Data from Federal agencies is decidedly more complete and accessible than from other entities. Such inconsistencies can lead to inaccurate conclusions if the limitations of the data are not understood.

Each subteam has produced one or more conceptual models of the processes operating within their area of interest. Collectively, these conceptual models create a rich tapestry that illustrates the extensiveness, complexity and interconnectedness of wildland fire. Along with the information summarized on existing analytical models and data sources, the conceptual models provide a strong foundation for building more rigorous models in Phase III that can be used to compare and contrast alternative strategies for reducing risk.

INTRODUCTION

The National Cohesive Wildland Fire Management Strategy (Cohesive Strategy) is an effort on behalf of Federal, state, local and Tribal governments and non-governmental organizations to collaboratively address growing wildfire problems in the United States. The Cohesive Strategy is being developed with input from wildland fire organizations, land managers and policy-making officials representing governmental and non-governmental organizations across all lands and jurisdictions. All stakeholders involved with wildland fire management have come together to develop a truly shared, national strategy. This holistic approach to wildland fire management will encourage further dialogue between local communities and national policymakers.

The intent of the strategy is to provide clear guidance on roles and responsibilities for all wildland fire protection entities. It also emphasizes how effective partnerships, with shared responsibility among stakeholders in the wildland fire community, will help maintain and restore landscapes, promote fire-adapted communities, and improve fire response.

The Cohesive Strategy is defined by three phases, allowing stakeholders to both systematically and thoroughly develop a dynamic approach to planning for, responding to, and recovering from a wildland fire incident.

The three phases include:

Phase I: National Cohesive Wildland Fire Management Strategy (completed)

Phase II: Development of Regional Strategies and Assessments (in progress)

Phase III: National Trade-Off Analysis and Execution (future)

The Cohesive Strategy will address the nation's wildfire problems by focusing on three key areas and goals with actions and outcomes:

1. Restore and Maintain Landscapes – Landscapes across all jurisdictions are resilient to disturbances in accordance with management objectives.

2. Fire Adapted Communities – Human populations and infrastructure can survive a wildland fire. Communities can assess the level of wildfire risk to their communities and share responsibility for mitigating both the threat and the consequences.

3. Response to Fire – All jurisdictions participate in making and implementing safe, effective, efficient risk-based wildland fire management decisions.

Multiple committees and teams have been formed in order to develop the Cohesive Strategy. These include the Regional Strategy Committees (RSCs) and their associated work groups, which are charged with setting objectives for each region, identifying key policy issues or choices, and ultimately outlining a range of options that might be employed within the region. The National Science and Analysis Team (NSAT) was created to provide analytical support to the RSCs and others. More specifically, the NSAT was established to support the development and implementation of the Cohesive Strategy through the application of proven scientific processes and analysis. To achieve this goal, the NSAT is charged with three primary tasks:

1. Assemble credible scientific information, data, and preexisting models that can be used by all teams working on the Cohesive Strategy.
2. Develop a conceptual framework that describes the relative effectiveness of proposed actions and activities on managing risks associated with wildland fire.
3. Construct an analytical system using the products developed in Tasks 1 and 2 to quantitatively analyze regional and national alternatives identified by regional and national strategy committees.

Tasks 1 and 2 were addressed within Phase II and will continue. Task 3 is exclusively a Phase III effort.

Organization of NSAT Efforts During Phase II

A wide range of individual scientists and analysts were invited to participate in the NSAT, representing federal, state, and tribal agencies, universities, and various non-governmental organizations (Appendix 1). The level of engagement has varied depending on individual interests, availability, and institutional support.

During Phase II, the NSAT has been working as a series of eight subteams, with each subteam assigned to a specific topical area. The topical areas were chosen to span the range of issues and processes involved in wildland fire, and to take advantage of the special interests and knowledge of NSAT members. The subteams include:

- Landscape resilience
- Wildfire ignitions and preventions
- Fuels management, wildfire extent and intensity
- Wildfire response and suppression effectiveness
- Fire adapted human communities
- Firefighter safety
- Smoke management and impacts

- Public acceptance and policy effectiveness

In this report, we have summarized and consolidated the efforts of the individual subteams. Subteam reports are available in their entirety at site to be determined.

Comparative Risk Assessment within the Cohesive Strategy

The Cohesive Strategy Phase I reports, *A National Cohesive Wildland Fire Management Strategy*, and *A Comparative Risk Assessment Framework for Wildland Fire Management: The 2010 Cohesive Strategy Science Report*, proposed comparative risk assessment as a structured process for evaluating the consequences of alternative wildland fire management strategies. As the Phase I report (p. 13) notes,

> *Risk is an inescapable component of living with wildfire. Whether one uses risk in the conventional sense of "something bad may happen" or a more precise definition such as the expected loss from an uncertain future event(s), the basic elements of uncertainty and loss are there. Following this basic reasoning, one can view the Cohesive Strategy as a classic problem of risk management. That is, effective management requires understanding the nature of wildfire and its contributing factors, recognizing the consequences—good and bad—of fire, addressing uncertainty, and crafting plans that reduce the chances of catastrophic losses. Real-world constraints on funding, available resources, and administrative flexibility further require consideration of economic efficiency and practicality.*

Given the premium placed on collaboration and engagement among all interested parties within the Cohesive Strategy, it is important that the quantitative aspects of risk assessment be embedded within a broader social discussion of values, options, potential consequences, and trade-offs inherent in any chosen strategy. To address this complex task of risk assessment and provide a structure for collaboration across the RSC's and the NSAT, an integrated decision support tool called CRAFT (Comparative Risk Assessment Framework and Tools) was employed. CRAFT is a structured process and set of tools designed to meet the needs of collaborative efforts to tackle complex resource management issues with conflicting values at stake and high levels of uncertainty. Planning teams are guided through a four-step process, broadly characterized as 1) specifying objectives, 2) designing alternatives, 3) modeling effects, and 4) synthesizing results. Each participant contributes to each step, although the roles played by analysts and scientists differ from that of managers and stakeholders (Figure 1). CRAFT is being used to help ensure consistency among regional strategy committees, using tools that have been specifically tailored for the Cohesive Strategy. CRAFT also provides the basic framework for the work of the NSAT.

Conceptual Overview of Wildland Fire

Wildland fire is a complex phenomenon that encompasses numerous interacting social, ecological, and physical factors. The Cohesive Strategy can be viewed conceptually (and simply) as a collection of management actions, policies, and activities, that collectively influence four major interacting processes: vegetation composition and structure, wildfire extent and intensity, response to wildfire, and community preparedness and resiliency (Figure 2). These processes in turn influence the goods and services received from forests and rangelands, firefighter and public safety, and homes and property affected by fire.

The NSAT subteam efforts built upon and expanded the components within the simple conceptual model presented in Figure 2. For example, the wildfire and ignitions subteam considered a broad range of factors that affect where, when, and how wildfires start and how various combinations of engineering, enforcement, and education can influence human-caused ignitions. Similarly, the fuels management subteam examined how various combinations of prescribed fire and other fuel treatments affect vegetation structure and composition, which in turn influence (and is influenced by) wildfire extent and intensity. Such interactions play out differently across different ecological biomes and at different spatial and temporal scales.

Due to the complexity of wildland fire, many of the identified factors necessarily overlap or intersect between and among topical areas. This is especially true for the more integrated issues such as landscape resilience, fire adapted human communities, and public acceptance and policy effectiveness. Given that the descriptions below are predominately conceptual, some ambiguity is tolerated in describing the various components and their interactions. As the conceptual models described here are translated into more quantitative models to be used in Phase III, the various components and relationships among them will be made more explicit—which will tighten the linkages between topical areas and improve overall precision.

Defining Resiliency

Fundamental to the restoration and maintenance of both natural and human-dominated landscapes is the concept of resiliency. Resilience literally means to “spring back.” Countless disciplines utilize the concept of resilience. In engineering resilience is the ability of a material to store or absorb energy without permanent deformation . There is an economic resilience that measures the ability of local economies to overcome business interruptions after natural disasters. Psychological resilience is used to describe the ability of individuals to recover from misfortune. Examples abound of other scientific disciplines relying on the concept of resilience.

In an ecological context, resilience was first introduced in 1973 by C.S. Holling. He defined ecological resilience as the amount of disturbance that an ecosystem could withstand without changing the self-organized processes and structures. Similarly, Walker et al. (2004) defines resilience as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks. The NSAT subteam working on fire adapted human communities used this definition in their work. For more general purposes of the Cohesive Strategy, we propose the following definition:

Landscape Resilience is the ability of a landscape to absorb the effects of fire by regaining or maintaining its characteristic structural, compositional and functional attributes. The amount of resilience a landscape possesses is proportional to the magnitude of fire effects required to fundamentally change the system.

Resilience in any context has been notoriously difficult to define, let alone quantify. In the current context, the basic question is whether the frequency, severity, and extent of wildfires likely to be experienced within a given landscape will be sufficient to cause substantive and perhaps irreversible changes in the character of that landscape. Resiliency thus defined is inherently contextual. That is, two landscapes can exhibit very different fire regimes yet have equivalent levels of resiliency. A temperate rainforest in coastal Alaska can be equally resilient as a fire-adapted sagebrush system in Nevada. Both maintain their character in the face of the fire regimes that they will likely encounter.

The challenge with resiliency can arise in two primary ways. First, there can be shifts in the fire regimes that arise because of climatic changes or anthropogenic influences. The new regime may be inconsistent with the existing character of the landscape and so adjustments in both the regime and landscape occur over time. Historical examples are common where either the climate has abruptly changed or human activities have either increased or decreased the amount of fire on the landscape. The results have been corresponding changes in the composition, structure, and pattern of dominant vegetation across the landscape. Such changes can lead to both transitional and long-term losses (or gains) in ecosystem services derived from these landscapes.

The second dilemma arises when fire regimes that are dictated primarily by climate and natural vegetation are at odds with human uses and values. The classic example is that of homes being built in the wildland-urban interface where wildfires are to be expected and cannot be excluded. Considerable effort is required to either protect homes from inevitable fires or fundamentally change the fire regime.

It is important to note that resiliency does not inherently imply value, i.e., favorable or unfavorable conditions. There is a natural tendency to think that resilient systems are preferable to non-resilient systems, but that is because the system in question is often one that we wish to maintain or preserve. Resiliency can be a barrier to achieving management objectives, however, when the management objective differs from the current conditions. The best examples of this situation are rangelands overrun by the invasive cheatgrass (*Bromus tectorum*) or southern pine forests infested with cogongrass (*Imperata cylindrical*). In both cases, the invasive grass changes the natural fire regime in ways that promotes further expansion of the species. The end result can be a highly infested system that is resilient to both fire (prescribed or natural) and other management attempts to eradicate it.

UNDERSTANDING WILDFIRE IGNITIONS AND THE ROLE OF PREVENTION

All wildfires start with an ignition, so it is appropriate to begin there. Wildfire ignitions can be broadly classified into two major categories: natural and human-caused. The vast majority of natural ignitions are due to lightning, whereas human-caused ignitions arise from a wide range of accidental and intentional activities. The most complete and accessible records of wildfire locations and statistical causes are for lands administered by Federal agencies. Similar records exist for many states and localities, but these records have not been consolidated with a degree of consistency that allows an accurate portrayal of trends across the United States. Summary statistics of fire activity on federal lands indicate that lighting is the dominant source of ignition on these lands, many of which are located in western states (Table 1). Such statistics do not mirror fire activity on other government or private lands, particularly in eastern states where human-caused ignitions play a much larger role on the privately owned lands that comprise the bulk of the landscape.

Biophysical variables

At the most basic level, fire is a physical process and many studies of ignition patterns have tried to incorporate biophysical predictor variables capturing the essence of that process. For a successful ignition to occur, the presence of fuels with low enough moisture levels to allow the combustion process to begin is required. Assuming fuels are present, moisture content is largely a function of temperature, solar radiation, humidity, and precipitation duration and amount. Consequently, variables capturing the variability of temperature, radiation, humidity, and precipitation are commonly used to characterize ignition patterns at varying spatial and temporal resolutions. A number of studies relate ignitions to daily weather conditions, fuel moistures, and fire behavior indices—whether measured at individual weather stations or inferred from satellite imagery. Other studies rely on monthly summary statistics of precipitation and temperature or other weather-derived variables and long-term climate averages to explain past ignition patterns.

Topographic exposure affects the amount of solar exposure and drying rates of moisture loss from fuels. Consequently, this predictor variable also is commonly included, especially in studies that used monthly weather summaries or long-term climate summaries. This may confound explanation when general vegetation type categories are used because it is uncertain if the topographic variables reflect topographic effects on fuel moisture or further differentiate vegetation types.

The potential impacts of climate change on ignition patterns are intuitive: if climate shifts are warmer and drier in a location, then conditions will be more favorable for ignitions in that location. However, climate change is not likely to result in such a simple, two-dimensional change in variables important to wildfire processes, particularly ignition processes.

Societal Variables

Human-caused ignitions are also heavily influenced by biophysical conditions but require the additional consideration of how humans interact with their landscapes to fully understand their patterns. Research by Butry et al. (2010a,b) and Prestemon et al. (2010) found that human-ignited wildfires in Florida depend on weather (fire weather indices, precipitation) in ways expected from theory. Presumably, higher counts of wildfire starts occur when fuel and weather conditions are favorable for fire spread.

Many studies have identified a number of variables emanating from society that are correlated with, or expected to affect, wildfires of various categories. Society influences the frequencies of wildfires of most causes in multiple ways. These range from altering land cover and fuel types, building roads and other hard surfaces that serve as transportation corridors, generating a subpopulation of individuals that intentionally set or who accidentally ignite wildfires directly through their work and leisure activities, and producing an infrastructure and operating a large collection of machines that can ignite wildfires accidentally through malfunctions or in the course of regular operation. From a wildfire reporting perspective, more people living on landscapes increases the possibility that an accidentally (or even a naturally) ignited wildfire is reported and therefore is included in a wildfire occurrence database.

Spatial and Temporal Ignition Patterns and Trends

Wildfire ignitions of various causes tend to be clustered in space and time and have been observed in the United States to be undergoing long-term trends. The clustering has been linked in the research to the presence of fuels, humans and their infrastructure, and it might also be connected to varying levels of wildfire prevention efforts, including law enforcement. Short-term trends can also be explained by human deviance, such as serial firesetting behavior by particular individuals in concentrated locations over short (multi-day) and long temporal scales. Long-term trends in wildfire occurrences may be attributable to climate change-related alterations in vegetation but also to more gradual changes in society. Gradual changes that might be connected to wildfire occurrence include those associated with the frequency of outdoor activities, rates and mixes of wildfire prevention efforts, the size of the active population of arsonists, land use patterns, smoking rates, evolving technology, and altered legal environments. There is also the possibility that improved wildfire investigation capacities have contributed to some of the observed changes in the mix of wildfires by cause. Clustering and trend information could be useful in making forward looking predictions of wildfire occurrences by cause when the analyst lacks sufficient data to adequately capture the hypothesized causal or driving factors behind them.

Fuels Management Effects on Ignitions

Land managers take a number of actions that are intended to affect wildfire occurrence, spread, and severity, in the interest of minimizing or maximizing or achieving an optimal combination of outputs given costs. These include efforts to manipulate the fuels that are required for successful ignition and spread, and actions intended to reduce the frequencies of ignitions. Although fuels themselves (structure, quantity, moisture content) might be connected to ignition success, there is limited understanding of the role that fuels management plays in wildfire ignition processes. For example, Butry and Prestemon (2010a) and Prestemon and Butry (2010) report an inverse statistical relationship between some human-ignited wildfires and the total area of authorized hazard-reduction prescribed burn permits in Florida. One possible explanation for this finding, however, is that burn permit requirements for prescribed fire are an effective form of wildfire prevention, thus reducing the likelihood of accidental fires of several causes.

Prevention

There has been scant research published in the refereed literature on the effects of wildfire prevention efforts. The National Wildfire Coordinating Group (1998), in its Wildfire Prevention Strategies publication, defines wildfire prevention to consist of administrative, education, enforcement, and engineering activities. The administration portion of wildfire prevention could be classified as long-term efforts to reduce unwanted wildfire, including such activities as planning, development of early warning systems, and training of wildfire prevention personnel. Education includes 26 activities, ranging from public service announcements to signage. Engineering consists of eight activities, ranging from the establishment of building and land use codes to hazard fuel reduction. Enforcement is broken into seven activities, including fire investigations and compliance checks. With such a long list of prevention activities that could affect human-ignited wildfires, statistical analyses are hampered by a lack of accurate and complete reporting and by analytical (statistical) problems that might arise due to high numbers of potential variables that could influence ignitions. Fire management agencies have typically done a poor job of collecting and archiving consistent data on wildfire prevention activities over long time spans and large spatial scales. This lack of consistent and long-term reporting makes scientific analyses of the effects of prevention difficult.

In spite of data limitations, some analysts have successfully quantified some of the effects of various prevention efforts on wildfire occurrences. Wildfire prevention education studies include those focused mainly on Florida and confined mainly to the education component of prevention (Butry et al. 2010a,b; Prestemon et al. 2010) in Florida. Studies of Incendiary wildfires (Prestemon and Butry 2005, 2010) found that law enforcement is effective at reducing incendiary fire starts.

A Conceptual Model of Wildfire Ignitions

The conceptual model (Figure 3) shows the primary linkages among wildfire ignitions with the various biophysical, societal, prevention, and management variables or drivers described above. Naturally, wildfire ignitions are the centerpiece of this model ('Wildfire ignitions' box) and are separated into three general categories in the conceptual model. Natural ignitions include primarily lightning-caused ignitions. Accidental ignitions are generally human-caused ignitions that were not intentional (including escaped prescribed fires), whereas arson ignitions are those that were generated with malicious intent. Among these three general categories, the occurrence of natural ignitions is largely beyond our control, but the frequency of human-caused ignitions can be altered through strategic prevention efforts.

The boxes connected to the "Wildfire ignitions" box in the conceptual model indicate the potential pathways through changes in human behavior and activities that affect ignition frequency or through alterations in the biophysical conditions necessary for successful ignition. Many of the variables listed in these boxes have been described above. However, several variables may affect more than just wildfire ignition patterns. For example, biophysical drivers have a large influence on fuels and fuel moisture conditions that determine whether or not ignition is even possible. These same variables also influence wildfire behavior and spread. Thus, to accurately characterize the patterns of ignitions and the mechanisms influencing them, it is critical that the wildfire ignition and behavior processes remain separated in modeling efforts.

Societal variables are present in the conceptual model as four general categories – income, development, demographics, and culture. These drivers are considered to be largely immutable by actions that land-management agencies can make, even though they may be influenced by more broad-scale local, state, and federal government policies. Development, whether measured through housing, population, and/or road density, provides a proxy measure of human use of the landscape, with the idea that more use will result in more ignitions. Income, demographics, and culture may also alter that relationship, including how often and what kinds of work and leisure activities occur in fire prone locations, but these variables are more likely to play a role in the extent to which prevention activities can be implemented and how well those activities are accepted by residents.

Prevention variables are subdivided into three categories: education, engineering, and enforcement. These categories are designed to capture the potential influence of management actions specifically designed to reduce the frequency of ignitions and/or wildfire effects. The fourth category of wildfire prevention, administration, is assumed to operate at a higher level for land and fire management organizations. Administration could be defined as activities and decisions that create a more efficient and effective wildfire prevention environment.

The pathways through which management variables affect ignition patterns are not always direct. The only land management action that directly affects ignition occurrence is through escaped prescribed fires, which can be considered as wildfires within our framework. Fuel treatments may alter ignition frequencies and spatial patterns by changing the structure and arrangement of fuels on the landscape, thus altering fuel types and fuel moisture conditions that influence ignition probabilities, though these same alterations are likely to have a greater influence on fire behavior and spread. Suppression could be considered as an ignition reduction action, but suppression generally occurs after successful ignition and ultimately alters the area burned by wildfires.

Recommendations for Statistical Modeling of Ignitions

The conceptual model provides a framework and the pathways that could guide construction of a probabilistic ignition model or wildfire production function. A random ignition model is always a simple option, but available scientific literature documents that the spatial and temporal patterns of wildfire ignitions can be characterized through a wide variety of predictor variables. If a wildfire ignition production function endeavor is developed for the Cohesive Strategy, we provide these recommendations:

- Use a proper statistical framework, particularly when relating counts of fires by individual causes to social, biophysical, and management drivers.
- Recognize differences among weekends, holidays, and seasonal variations in wildfire occurrences when modeling at fine temporal scales.
- Recognize and explicitly account for long-term trends in various wildfire causes.
- Use separate models for each ignition source, at a minimum natural vs. accidental vs. arson.
- Include biophysical variables that capture weather and fuel moisture conditions appropriate to the temporal resolution of the models.
- Social and prevention and management variables should measure or be proxy measures of things that can be directly manipulated.

- To account for the effects of fire prevention, take advantage of the range of data that are available.

Furthermore, the historical coverage, completeness of coverage within covered time frames, accuracy of cause attribution, and spatial accuracy of the ignition location varies greatly among the various data sets available. Models that are applicable to particular locations or agencies, require at least a minimally reliable data set. Even if flawed, such analyses might allow for a first approximation that could be built upon or coupled with other datasets in developing a reliable, forward-looking model.

Proactive Fuels Management and its Influence on Wildfire

Given a sustained ignition and the absence of active suppression, three major components jointly drive wildfire behavior: topography, weather, and fuels. Fuel conditions and ignitions are the two primary drivesr over which humans can exert meaningful control prior to the wildfire event. Proactive fuel management seeks to alter the quantity, spatial arrangement, structure, and continuity of fuels so as to induce desirable changes in fire behavior should a wildfire occur. Two fundamental conditions exist for a fuel treatment to function effectively: first, the treatment must spatially interact with an actual wildfire, and second, the treatment must mitigate fire behavior according to design objectives. Broadly speaking, fuel management activities are designed to reduce the risk of catastrophic fire, protect human communities, reduce the extent and cost of wildfires, and restore fire-adapted ecosystems. Translating these policy goals into field-based implementation can be guided by adhering to a formal decision process:

1. Identify specific problems to be addressed by fire/fuels management.
2. Identify cause of problems as relating to fuels or fire behavior.
3. Describe desired outcome of treatment measure (how much change in fuel or fire behavior is necessary).
4. Identify appropriate scale of treatment needed to effectuate desired outcome.
5. Describe specific cause and effect relationship between desired outcome and proposed treatment(s).

A comprehensive review of the fire behavior modeling, vegetation modeling, and spatial analysis systems used by fuel management analysts, as well as published reviews of models and use, concluded the following:

- Relatively few existing fire behavior models are suitable for addressing specific analysis requirements for risk assessment and fuel management projects; most models were developed as part of basic fire behavior research.

- Every fire behavior model has a unique data input and output format; these data are not widely available for all models.
- Planners require both stand and landscape fire behavior modeling tools to test stand prescriptions and landscape effectiveness of fuel treatment packages.
- Most fuel treatment projects have multiple objectives and constraints that must be integrated with the analysis of fuels and fire behavior.
- The bulk of the analysis process for fuel treatment projects did not involve fire behavior modeling, but rather organization and processing of a wide spectrum of data within GIS to meet the broader resources analysis requirements of the project.

Similarly, a comprehensive review of fuel treatment effectiveness found the following:

- Fire effects on the overstory trees are most effectively mitigated by treatments that address both surface and crown fuels through combination treatments such as thinning followed by a prescribed burn or by removing slash after thinning.
- Prescribed burn treatments vary in effectiveness and become less effective with time since treatment (importance of maintenance, especially as more areas are treated).
- The importance of spatial arrangement and spatial heterogeneity of fuels and fuel treatments is poorly understood (mosaics, edge effects).
- Fuel treatments are not designed to stop fires but rather to modify fire behavior (e.g., reduce crown fires, enhance suppression and firefighter safety, achieve desired ecological benefits, etc.).
- Fuel treatments' effects vary with weather and can inadvertently exacerbate undesirable fire behavior under certain conditions (e.g., treatments may spur understory growth, which favors spread; they may permit higher wind speeds, which increase flame length and spread rates).

Thus the limited state of fuel treatment decision support (with exceptions e.g., ArcFuels), paired with limited information on fuel treatment effectiveness in modifying wildfire behavior challenge analysis of fuel management alternatives from project to landscape scales. That said, there is much to be learned in fuel treatment design and implementation from the many years of experience gained by forest and rangeland managers who manage vegetation for other objectives. This experience combined with modeling provides a basis for sound principles of fuels reduction.

The report of the fuels management subteam addresses in more detail many of the issues important for evaluating fuel management programs, including: (a) conceptual representations of wildfire behavior, extent and intensity and their relation to fuel and vegetation conditions; (b) qualitative descriptions of how fuel management alternatives can affect wildfire extent and intensity; (c) evaluations of existing models and data for prospective policy and scenario analysis; (d) regional illustrations of strategic fuel planning; (e) review of limitations challenging fuel treatment analysis and implementation; and (f) identifies informative references for assistance in developing and evaluating regional fuel management policies. The focus of this section is to synthesize and distill information useful for evaluating fuel management opportunities within the context of the Cohesive Strategy. Specifically we provide and review: (a) a conceptual model for evaluating the consequences of fuels management; (b) a workflow of the strategic fuels treatment decision process; and (c) decision frameworks and taxonomies for designing fuel treatment strategies premised on comparative risk assessment.

A Model for Fuel Management Planning and Decision-Making

Fuels management occurs at unit and landscape scales. Decision variables at the unit scale deal largely with specific vegetation management objectives and their relation to fire behavior metrics such as intensity, crown fire potential, and rate of spread. These metrics can in turn inform estimates of first- and second-order fire effects. Decision variables at the landscape scale deal largely with the frequency, magnitude, and especially the spatial pattern of treatments, which in turn are related to both to the spatial pattern of values at risk and the predominant fire risk factor (intensity, spread, etc.). Timing is another key variable, and most treatments require maintenance in order to offset re-growth and fuel accumulation.

Figure 4 displays the “big picture” conceptual model, which graphically illustrates the relationship between fuels management, fuel conditions, and wildfire behavior, extent and intensity. Driving variables are separated by color according to whether we can exert meaningful control, and boxes/ovals highlighted in red correspond to other National Science and Analysis Team (NSAT) sub-teams (Ignitions and Prevention; Fire Adapted Human Communities; Smoke; Landscape Resilience, etc.).

Figure 5 displays a conceptual workflow for the strategic fuels treatment decision process. Ultimately all management activities are driven by desire to achieve a goal and a need for intervention to achieve that goal. In step 1 this planning context is defined, wherein treatment objectives are articulated and analytical needs are outlined. For planning across large landscapes this could entail evaluating treatments spanning multiple ownerships, necessitating a transparent process for inclusion and consideration of stakeholder objectives. Steps 2-4 comprise the basic elements of wildfire risk analysis: geospatial data management, wildfire behavior simulation, & fire effects analysis. Step 5 entails the design of treatment strategies as well as analysis of their impacts beyond immediate changes to fuels and fire behavior (e.g., smoke production, biomass utilization). Steps 6-8 correspond to steps 2-4 (wildfire risk analysis) under the hypothetically changed fuelscape. An iterative process repeating steps 5-8 evaluates the impacts of various alternatives and seeks to learn from analysis results to design optimal treatment strategies.

Strategic Fuel Planning

While the field application of non-spatial fire behavior models (e.g., BehavePlus) for a single fuel type and constant weather conditions is relatively straightforward, the design and evaluation of large-scale risk assessment and fuel management activities requires more complex landscape fire modeling to fully understand the potential benefits of fuel management proposals.

Landscape fuel treatment involves a tradeoff between treating more areas of the landscape at least once and repeatedly treating a more limited area to maintain treatment effectiveness. Funding limitations and multiple other constraints limit our ability to implement treatments at broad scales across landscapes, necessitating a strategic approach to treatment design and placement in order to cost-effectively limit fire spread and severity, while also meeting other management objectives as appropriate. Primary variables involving the coordination of stand-level treatments across a landscape include the size of individual treatment units, the placement/pattern of the treatments, the proportion of the landscape treated, and treatment longevity. Important constraints including habitat preservation (and the issue of trying to reduce fire behavior within areas where treatments are largely prohibited), human communities (affects placement priority and limits prescribed burning), air quality concerns, regulation and appeals, and economic realities (influenced by variables such as amount of merchantable material harvested, end-use of harvested material (timber markets, biomass, etc.), terrain, and treatment type). Collectively these constraints can hinder the effectiveness and limit application of optimally located treatment patterns, and generate uncertainty over whether it will be possible to effectively treat the area recommended by fire modeling studies.

A realistic process for landscape-scale fuel treatment would identify feasible management opportunities and pair that information with risk-based analysis of fuel management needs. Management opportunity can be defined temporally (burning windows, treatment longevity, etc.), spatially (ownership, restricted areas such as critical habitat, etc.), and economically (availability of funding, and whether they may yield positive net benefits). Prior definition of the spatiotemporal “box” within which fuel treatments can be implemented allows for informed prioritization and planning efforts. Key decision variables are the spatial pattern and magnitude of treatments, the extent of the landscape treated, and the timing between re-entry. Important questions driving strategic fuel planning include:

- Is the treatment intended largely for restoration or protection objectives?
- If protection, what is the spatial pattern of values at risk and what is their response to fire?
- If restoration, what is the target fire regime and how can it best be achieved?
- How likely is the area to interact with fire?

- What is the predominant risk factor of concern (fire occurrence, spread, intensity, etc.)?
- How do the planned treatments align with other resource objectives?
- What is the nature of the planned engagement with suppression response?
- Where are opportunities for leveraging with existing fuelbreaks (roads, water bodies, previous burns, etc.)?

Apart from a limited set of instances where wildfires opportunistically interact with fuel treatments, evaluation of landscape-scale fuel treatments is largely a modeling exercise. As such, results of modeling experiments have been characterized as hypotheses that are waiting to be tested. Typically landscape modeling attempts to characterize where/how fires are likely to spread and the subsequent impacts, considering heterogeneity in topography, vegetation, land uses, and land management objectives. ArcFuels in particular has emerged as a useful tool for risk-based fuel treatment evaluation, leveraging the FVS growth and yield simulator with a suite of fire behavior and growth models within a GIS environment.

Results of modeling studies provide insights that can guide future planning and implementation. Perhaps most important is the realization that while targeting high hazard stands may reduce severity within treated areas, the treatment may not affect broader landscape fire processes. That is, the benefit of the treatment might be limited only to the area treated. Strategically placing area treatments within a matrix of untreated areas can slow the spread of a large wildfire or cause a drop in intensity across a larger landscape, thus reducing severity in both treated and untreated areas. The synergist effect of a broader landscape strategy can outweigh the more direct benefits of treatments concentrated near values at risk in some circumstances.

Earlier work outlining the scientific basis for the Cohesive Strategy described comparative risk assessment as a basis for guiding field-level fuel treatment planning consistent with policy objectives. Figure 6 presents a conceptual overview of that risk-based process, in which overall fuel and fire management strategies are developed through jointly evaluating fire likelihood, intensity, and potential effects combined with spatial patterns of values, fire management objectives, and fire regimes. Risk analysis entails understanding the likely interaction of valued resources with wildfire activity (e.g., probability of occurrence, fire intensity and severity), and estimating the nature (beneficial/detrimental) and magnitude of resource response to fire. Fire management objectives consider ecological conditions and determine the extent to which long-term risk management will emphasize restoring natural fire regimes or will emphasize resource protection via hazardous fuels reduction and suppression. Lastly, management opportunity dictates the spatiotemporal extent to which treatments can be implemented consistent with management goals and funding constraints. Management activities and implementation of fuel treatments then stem from the selected mitigation strategy.

Figure 7 displays some example scenarios that cover a range of fuel treatment strategies and fire restoration management objectives. Variables implicitly considered within the treatment strategy include engagement with suppression and the cost-effectiveness of treatment types. For instance with the first column (low severity fire regime) treatments are planned to create conditions under which suppression efforts are largely unnecessary, whereas with the last row (high severity) treatments (fuel breaks) are specifically planned for engagement with suppression resources. With respect to the latter category, recent work in in southern California demonstrated that fuel break effectiveness was directly tied to interaction with suppression activities. Recognizing the divergence in management objectives and spatial treatment needs enables optimization approaches to move beyond strategic placement of area treatments (SPLATS; see the 2nd column mixed severity) to optimally locate treatments to achieve a variety of objectives.

Response to Wildfire and Suppression Effectiveness

Nearly all wildfires in the Unites States elicit some form of active response. In the vast majority of cases, the intent of the response is to safely contain and extinguish the wildfire as quickly and effectively as possible. In certain circumstances where wildfires can be used for beneficial purposes, the response may be to primarily monitor the fire and ensure that public safety or valued resources are not threatened. Wildfire response and suppression has three temporal elements: pre-fire, during fire, and post-fire. The pre-fire stage includes all planning, fuels management, pre-positioning, training, and funding in preparation for a fire event. Active suppression tactics and associated management decisions are relevant during an event. Post-fire actions examine the consequences of the event, feeds into socioeconomic and policy arenas, and builds collective experience.

Interactions among the various components of response and suppression can greatly influence the success of management actions at each stage in the process. These interactions can be portrayed within a conceptual model that was built to better understand systemic relationships and inform potential process improvements (Figure 8). The different shadings of the factors influencing wildfire response and suppression represent differing degrees of point-wise control of the system. The solid dark blue shading is used for actions that are controllable by and through management. The translucent shading is for factors that are partially controllable or can be mitigated to some extent, and the white background depicts factors that are not controllable or cannot be mitigated over a reasonable management horizon. Arrows depict relationships between the factors, described below.

Uncontrollable factors

Uncontrollable factors in the conceptual model include location and topography, and weather and climate. Location and topography refers to the geographic and geomorphic site characteristics that a manager must contend with. Remote wildfire locations or areas with terrain that is difficult to traverse on the ground clearly influence tactical decisions—both during a fire event and when preparing for a possible fire event. Location and topography also influence fire intensity and extent. Sloped terrain and areas prone to wind may enhance fire intensity and spread rate, but the terrain may offer natural fire breaks as well.

Weather and climate also strongly influence fire intensity and extent, and provide conditions for ignitions. Having advanced knowledge of fire weather enables better pre-positioning of assets for initial attack.

Partially controllable factors

Partially controllable factors fall somewhere between completely controllable and completely uncontrollable factors, meaning that there are unavoidable random processes in play that can thwart management intentions. Fuels and ignitions fall into this category for many of the reasons described in preceding sections. Fire intensity and extent is partially controllable through suppression, but variability in weather, fuels, location, and suppression effectiveness all contribute to reduced management control. The uncertainty in fire intensity and extent naturally carries forward into uncertainty in consequences.

Several partially controllable factors directly influence suppression capacity and placement and expectation of consequences. Among these, socioeconomics and policy is viewed pragmatically in the model, meaning that optimal policies are not necessarily a given, and the interplay between demographics, zoning, local economies, and local community acceptance cannot be predetermined with certainty. Funding relies on public and private allocations and policy directives. Again, since these inputs are not completely controllable or known with certainty, neither can funding levels be known with certainty. Funding is broken into two categories: capacity investment and operational. Capacity investment refers to asset purchases and infrastructure changes. Operational funding refers to maintenance, staffing and tactical planning. Finally, the transport network is viewed as fixed in the short term but can change based on infrastructure investment or lack thereof. Since funding levels are uncertain, so too is the existing transport network.

Controllable factors

Although realistically no factor can be perfectly controlled or predetermined, perfect control is assumed here for the sake of model simplicity. Of the 17 factors identified in the conceptual model, only 7 of these factors are seen as completely controllable. Among these, fuels management refers to treatments and spatial locations of such treatments (addressed above). Similarly, prevention and law enforcement are management choices that directly influence ignitions as described above.

The expected consequences factor represents management's expectations of a given situation. More specifically, expectations could refer to a given fire event—thus soliciting a given suppression response; or expectations could refer to gains in preparedness through training or asset pre-positioning.

Suppression capacity and placement is assumed to be known with certainty. That is, for a known budget, known transport network, complete knowledge of assets and using standard performance measures of different types of assets, suppression capacity is well defined. Placement (meaning location of the home base of an asset) and pre-positioning (meaning a temporary displacement of an asset away from its home base) are also assumed to be under complete control of a planner/manager.

Actual suppression response is assumed to be controllable. In reality, suppression response for a specific fire event may not be completely controllable for an incident commander if requested resources are not available. This could occur during multiple fire days when demand for assets exceeds supply. Yet at any given location, a hierarchy of dispatch rules is assumed known and completely controllable.

Training leads to increased knowledge and experience, which in turn influence suppression capacity and placement and active suppression response.

Effectiveness and functional relationships

How effective management is for any controllable or partially controllable factor depends on management's intentions or objectives. Effectiveness is therefore defined as the deviation between management objectives and the actual outcome. This definition permits evaluation of effectiveness for any controllable or partially controllable factor, and metrics can be defined uniquely per factor.

The connectedness of the various factors implies that the degree of effectiveness at any particular factor depends on the degree(s) of effectiveness for all its contributing factors. In other words, effectiveness is a cumulative function, and how well objectives match outcomes at any particular level is influenced by how well objectives met outcomes at upstream levels, and so on. This phenomenon of nested effectiveness is significant. It implies that the effectiveness of downstream actions is constrained by prior outcomes. Further, this structure enables planners to anticipate where potential threats may be and take advanced action.

In all, a holistic cohesion can be shared across individual players to improve overall system performance. The conceptual model can also help identify factors that lead to cost savings, improved firefighter safety, etc. Any investment in the system is tractable, and the return on investment in one or more factors can be measured through the system.

Coordination of resources

Implicit in the conceptual model is coordination between Local, State, Tribal, and Federal resources. Across the nation, a range of formal agreements between organizations have been established. Because threat levels, ownership patterns, and asset mixtures are different from one geography to the next, so too are the arrays of agreements. Preliminary analyses using the initial response model of the Fire Program Analysis (FPA) system clearly demonstrates that multiagency coordination and sharing of resources can lead to reduced response time, bring more resources to bear on individual fires, and substantially improve initial response success rates. Similar efficiencies might be expected for extended attack on larger fires, although the increased complexity of such events compounds the difficulty of modeling large fire responses.

Quantitative Modeling of Wildfire Response

Analyzing investments in wildfire response can be very complicated. In addition to the complexities of fire behavior, one has to address interactions among the distribution of available resources, their performance on the fire, the dispatch logic used to send resources to a fire, and multiple operational constraints. FPA includes a highly detailed Initial Response Simulator which addresses many of these issues, but is designed to only simulate responses in the first 18 hours following discovery of a wildfire. Although 18 hours may seem brief, in reality the vast majority of wildfires are suppressed during this initial window. Extending FPA modeling capacities beyond the federal resources is challenging due to the very large number of local and state resources involved in wildland fire response. Thus it is likely impractical to expect to use FPA models directly. A more promising route may be use combinations of FPA modeling results, empirical fire occurrence data from all localities, and expert opinion to build simpler models that capture the essential elements of initial response.

Simulating initial response not only demonstrates the effectiveness of investments in preparedness, it also is essential to understanding the feedback between initial response effectiveness and behavior of fires that escape. Highly successful initial suppression efforts means that fires escape only under the rarest and most extreme weather conditions, becoming more severe. Thus, the long-run potential benefits accruing from having a greater share of wildfires burning under moderate conditions are never realized. The end result is that effective initial suppression in the short run leads to greater demands for initial response resources in the long run. Through more detailed analysis and the modeling, this feedback process may become understood and incorporated into the risk framework.

Once a wildfire has escaped initial containment efforts, further complications arise as resources are drawn from remote locations, fire behavior becomes difficult to predict, and even the objectives of the suppression response may change from day to day depending on circumstances that are not easily understood or modeled. Recent research focused on understanding the factors contributing to the high costs of large fire suppression offer insights that could be used to more rigorously structure the relationships identified in Figure 8. In addition, ongoing research directed at better understanding the management context and decision processes used in large fire suppression may lead to more reliable models that can capture the principal factors influencing performance—however it might be measured.

Fire Adapted Human Communities (FAHC)

The significant social and economic costs of recent wildfires draw attention to the need to understand society's exposure to wildfire impacts. Wildfire impacts are thought to be increasing for a number of reasons, including decades of fire suppression, climate change and drought, and an increase in the human populations at risk from wildfires due to the rapid expansion of the wildland urban interface (WUI). These factors contribute to devastating losses to individuals and communities in lives lost and homes and other values damaged or destroyed, as well as substantial expenditures by the members of the fire management community.

Here we concisely document our understanding of the various characteristics, relationships, and factors that affect a community's vulnerability and resilience to wildland fire threats. This summary is necessarily brief, recognizing that various issues or topics that are regionally important may have been minimized or omitted due for the sake of brevity. The intent is to capture the primary drivers affecting communities' exposure to risk from wildfire. A secondary objective is to conceptualize the problem so that it can be quantitatively or semi-quantitatively modeled in Phase III. Potential data sources are identified as a suggestion or starting point of how to implement a Phase III FAHC model.

Background

A fire adapted human community is one where the population, natural capital, and built infrastructure can withstand a wildland fire without loss of life or significant damage; and where the community can assess their wildfire risk, share responsibility for mitigating threats, and accept the consequences according to their risk tolerance. Similarly, communities "foster a fire resilient landscape"and acknowledge that their community actions play a role in affecting the larger socio-ecological systems in which they are embedded. To describe the elements of a fire adapted human community, we use specific terms from the vulnerability literature (ecological and social), including:

Exposure: the nature and degree to which a community, individuals, assets, or other values are threatened by a hazard.

Vulnerability: (social and community) the culmination of social factors and forces that create the susceptibility or exposure of various groups to a hazard (Cutter et al. 2003); (physical and ecological) the degree to which a system is susceptible to, or unable to cope with, adverse effects of wildland fire.

Preparedness: a continuous cycle of planning, organizing, training, equipping, exercising, evaluating, and taking corrective action in an effort to ensure potential losses are minimized.

Research from the fields of wildland fire social and behavioral science can inform our understanding of fire adapted human communities, their response to, and mitigation of, wildfire threats. Yet much remains unclear in this relatively young area attempting to understand complex human behavior and actions. For example, an important question is why individuals choose to participate or not in wildfire mitigation activities on their property. Using fire-safe landscaping, construction materials and techniques, and developing and maintaining defensible space are actions that significantly improve the chance of a structure surviving a fire, yet the reported responses of individuals is mixed in the literature with varying levels of participation. Common elements influencing homeowner decisions include risk perception, ecological or amenity values, the cost and time of creating defensible space, and social pressures (McCaffrey et al. 2011).

At the community level, there are examples of apparent trends in community vulnerability and participation in wildfire risk mitigation programs. Studies in Arizona and the Southeast indicate that vulnerability and exposure to wildfire hazards are positively related based on a comparison of indices of vulnerability and wildfire threat with participation in Community Wildfire Protection Plans (CWPP) or Firewise Community designations (Gaither et al. 2011; Ojerio et al. 2011). These analyses provide methods that could be used in CS Phase III to highlight areas needing increased education, outreach, or other program actions, or to address potential equity or environmental justice issues.

On the threat side, many advances in wildfire modeling (described above) can provide important data to determine the risk facing communities from wildfire. For example, wildfire ignition models can simulate the occurrence of wildfires across space and time, including their clustering tendencies. In turn, fire behavior models can simulate the burn probability, direction, and conditional flame length at a national extent for any given pixel on the landscape.

These data can then be used to identify structures, population, and other values at risk. Operation decision support systems like the Wildland Fire Decision Support System (WFDSS) already have this capability at the landscape scale and are used to strategically deploy fire response and suppression resources. Our understanding of FAHCs and the proposed methods to be developed in Phase III will hopefully aid wildland fire management by illustrating how programs and actions can reduce the exposure of human communities to wildfire threats, thereby making them more fire adapted.

Characteristics of fire adapted human communities and mitigation actions

A FAHC can decomposed into the primary components of individual and household elements, community elements, and physical and environmental elements (Figure 9). The combination of these elements and their interactions leads to a community being more or less fire adapted. Household preparedness is the level of knowledge and planning in preparation for a potential wildfire. Social vulnerability refers to the factors influencing individuals that may make them more susceptible to adverse effects of wildfire. Community vulnerability describes emergent vulnerabilities at the community level, which may be affected by economic resilience and community social capital, for example. Institutions and governance describe government policies and programs or informal social norms that influence actions pertaining to exposure to wildfire threats. Neighborhood characteristics describe the spatial pattern and arrangement of structures on the landscape in relation to wildfire threats, while structure characteristics depict the construction materials used. Ecosystem services are the benefits to society from natural capital, and may be affected positively or negatively by wildfire and mitigation activities. Not shown, but implied, are the complex interactions among elements.

Mitigation and management actions affect the characteristics of FAHCs by pushing them in the direction of a more fire adapted state. This can occur, generally, in three phases. Similar to McCool et al. (2006), we describe actions affecting communities by time horizon, and classify actions as occurring pre, during, and post wildfire event (Figure 10). As in the previous figure, actions listed are broad and may include multiple specific actions or existing programs. Examples include education and outreach, communication and information management, or post-fire assessment of fuel treatments. These actions do not constitute the entire suite of potential wildfire mitigation possibilities, but rather a representative set of primary actions used to affect the characteristics of FAHC and their exposure to wildfire hazards.

The specific characteristics these actions affect are outlined in the Fire Adapted Human Communities Phase II Report, and are organized according to the groups in Figure 9. Actions and programs affect individual, community, and physical and ecological elements, though not all characteristics can be changed within the timeframe or by wildfire programs. Understanding social vulnerability, for example, can influence evacuation planning, but wildfire programs do not address the underlying causes of social vulnerability. Figures 11 and 12 clarify which characteristics can be altered by wildfire programs by pre, during, and post event period.

Phase III Modeling

The FAHC model will likely be most useful as an exposure assessment using our conceptualization of a FAHC and wildfire hazard data from other subgroups and sources. Bayesian belief networks will describe the conditional probability of the intersection of FAHC elements and wildfire threats, illustrating the location and heterogeneity in risk across the nation. Quantifying the diagrams with comprehensive and current data in a tradeoff analysis or influence diagram will be challenging. A flexible, semi-quantitative modeling environment will likely be required as deterministic causal relationships will be difficult or unrealistic to establish. Expert knowledge could be used to judge the potential impact of programs or actions on FAHC characteristics. Though research assessing the social aspects of communities' risk to wildfire is scarce at the landscape or national level, the creation a FAHC model in Phase III will be aided by several ongoing efforts, including Haas et al. (in review) who demonstrate a method to assess the risk of wildland fire to populated places, and FEMA's HAZUS program which estimates potential hazard losses from earthquakes, hurricanes, and floods. Several potential data sources include:

- Landfire, Finney et al. (2011), and data and output from other sub-teams;
- Census 2010 for demographic information;
- ESRI Community Analyst and Tapestry Segmentation products;
- Landscan & Haas et al. (in review);
- WFDSS data on various values and infrastructure at risk;
- FS data/methods to determine the natural resource dependence of a community;
- Insurance data: ratio of insured/total in a community, possibly from IBHS;
- Location of CWPPs, Firewise designations, State Fire Assistance grants, and NFP actions;
- HAZUS data and methods for physical damages, economic losses, and social impacts from hurricanes, earthquakes, and floods. FEMA Loss Avoidance Study: Wildfire Methodology Report;
- Ecosystem services: Carbon stocks from Land Carbon project, Woods Hole Research Center, methods from (Hurteau et al. 2008; Hurteau & North 2009; Ager et al. 2010a); InVEST models to determine the value of other services (InVEST user's manual or website).

Firefighter Safety

Wildland firefighter safety holds an important position within the Cohesive Strategy. To achieve each of The Cohesive Strategy's broad objectives—landscape resiliency, fire-adapted communities and effective wildfire response—wildland firefighters are on the front line. Wildland fire personnel conduct the fuels treatments that enhance and maintain landscape resiliency, work with the public to reduce community risks from wildfire, and often put their lives in jeopardy when responding to wildfires. Firefighters bear many of the health and safety consequences of how society deals with fire.

Firefighters die or are injured during driving and aviation activities, from burnovers and other line incidents, and for medical reasons related to work stress. Repeated exposure to smoke and other environmental hazards can have additional implications for long-term firefighter health. While most of these occupational hazards are partially mitigated through training, safety equipment, and incident management, a synthetic and cross-jurisdictional understanding of how injuries and fatalities are affected by broad fire management strategies is lacking. This section summarizes some of what is known about wildland firefighter health and safety issues and presents a conceptual understanding of the various factors that decision makers can and cannot control. Framing firefighter risk within a network of causes conveys how individual solutions may be only conditionally effective. By building a conceptual understanding of this broader problem, solutions are more likely to be successful.

What causes firefighter injuries and deaths?

Two approaches are commonly used to learn from past firefighter injuries and fatalities. Narratives provide detailed descriptions of the context and consequences of fire management activities involving safety incidents, and statistical summaries provide insights into the importance of hazards by causal categories. When causes are summarized by region, patterns emerge that appear to be consistent with differences in wildland fire response operations (Figure 13). Aviation and entrapment (which includes burnovers) are proportionally more common in the West where wildfires are larger and often on Federal lands, while driving and overexertion (which includes heart attacks) are more common in the East where small fires are numerous, and local fire departments have less strict age and fitness standards. To formally capture such causes behind the statistical cause, a third approach that relies on conceptual models is useful. Conceptual models integrate the richness of narratives, with the categorical simplicity of databases. Graphical conceptual models show the primary direct and indirect cause-effect relationships that exist from environmental factors and pre-fire, during-fire and post-fire management decisions. The conceptual models described here have been designed to be broadly applicable across jurisdictions and geographic regions.

The NSAT subteam working on firefighter safety created separate conceptual models for incidents involving aviation, driving, burnovers, hazard trees, heart attacks, smoke and long-term firefighter health (see full subteam report for more details). Figure 14 shows an integrated conceptual model for all incident hazards. Hazardous exposure is influenced by fire attributes and job assignment; the consequences of that hazard are mitigated by improved situational awareness and firefighter response. This model also shows the primary means by which uncontrollable drivers contribute to the hazards that firefighters face.

Long-term health issues for firefighters can result from incremental exposure to hazards during repeated events or seasons. These hazards include the cumulative effects of smoke or hazardous silica exposure from wildland fires, chronic problems caused by repetitive motion, hypersensitivity to toxic plants from repeated exposure, and an elevated skin cancer risk from extended sun exposure.

In Figure 15, long-term health is influenced by cumulative exposure which in turn is influenced by hazardous duty assignments, the characteristics of fire events, and how hazards on individual fire events were mitigated. Awareness of the risks of long-term exposure can be improved with monitoring equipment, better training, and improved incident management.

Long-term firefighter health can involve changes in firefighter sensitivity to hazards over time from exposure, but this is conditional on genetic and other attributes of individuals. Long-term health monitoring and early intervention can mediate long-term health, as can fitness, lifestyle choices and genetics factors that are hard to manage except through screening.

Management strategies conveyed by conceptual models

Conceptual modeling of incident risks suggests that multiple pathways exist for reducing firefighter injuries and fatalities. These can be grouped as efforts that emphasize improvements in the firefighter workforce, refinements in the way fire incidents are managed, and changes the attributes of wildland fire (Table 2). The pathway that targets the workforce could involve improved personnel screening and fitness programs, better training, greater work experience and better equipment. Each of these solutions would occur before the fire occurs.

A second pathway for reducing injuries and fatalities is through changes in incident management during the fire. Incident decisions drive job assignments, which involves the use of direct and indirect suppression tactics and therefore exposure to hazards from falling trees, burnover, smoke, stress, and aviation factors. Continued improvement of fire behavior modeling tools and post-fire learning can make such incident decisions more effective.

A third pathway for reducing injuries and fatalities involves changes in the number, size, duration or intensity of wildfires. This strategy involves wildfire prevention, fuels treatments and other efforts that influence firefighter exposure in ways that are consistent with the Cohesive Strategy goals of increasing landscape resilience and fostering fire adapted human communities.

Existing data and prospects for quantitative modeling

A diverse range of firefighter health and safety data exist. The US Department of Homeland Security's National Fire Administration (NFA) and the Fallen Firefighter Foundation support a database that includes both structural and wildland firefighter fatalities. The National Wildfire Coordinating Group (NWCG) in association with the Wildland Fire Lessons Learned Center collects and reports both fatality and injury data. The simple number of injuries and fatalities sustained during large incidents are included in 209 reports for individual fire events, although these incidents lack detail. Several parallel efforts provide incident narratives which are more useful for conceptualizing the problem than for modeling or analysis. Injury data exist from similar USDA Forest Service and USDI efforts, although these only address Federal incidents. Safenet and Safecom are interagency efforts to address unsafe conditions and report mishaps involving fires and aviation issues, respectively. No existing efforts systematically document long term health effects.

In quantitative modeling that explores different management scenarios, aspects of firefighter safety could be linked to results from fire behavior and smoke modeling efforts through the concept of exposure. Useful variables include fire attributes such as size, duration, and behavior, which are affected by landscape fuels treatments, fire ignitions (and prevention efforts) and climate scenarios. Linking job assignments with simulated fires and incident management decisions may be more difficult. Hazard mitigation is also difficult to model, as it involves factors such as communications, training and equipment that may be best modeled as a workforce mitigation factor. Changes in firefighter screening or fitness could drive the number of age or fitness-associated fatalities.

Long-term firefighter health is most difficult to model due to the broadened complexity of the issue and a general lack of data. Creative approaches could be developed that estimate cumulative exposure from changes in the distribution of fire intensities, durations or numbers that result from different management scenarios.

SMOKE MANAGEMENT AND IMPACTS

Smoke has the most far reaching impact of wildland fires. Smoke from wildfires can easily affect air quality hundreds, even thousands of miles from the source, affecting millions of individuals. While large wildfires often have the most far reaching impact, the frequent use of prescribed fire as a management tool to reduce the risk of large wildfires also can have adverse smoke impacts.

Smoke impacts can generally be characterized into two classes, visibility related and health related. Visibility impacts range from regional haze that obscure general visibility and degrades scenic vistas, to dramatic visibility reductions that creates a hazard to both air and ground transportation. Health related impacts are regulated through the National Ambient Air Quality Standards (NAAQS) outlined in the Clean Air Act. The Clean Air Act is at the core of most air quality regulations and is designed to protect humans against the adverse health effects of air pollution. The U.S. Environmental Protection Agency (EPA) is charged with implementing the Clean Air Act and sets limits on the allowable concentrations of various pollutants through the National Ambient Air Quality Standards (NAAQS). The purpose of NAAQS is to establish quantitative pollutant concentrations that serve as thresholds above which detrimental effects to public health or welfare may result. State regulations add to the intricate web of interrelated laws and regulations addressing smoke.

The primary pollutant of concern for forest fire smoke is particulate matter (PM10 and PM2.5; particulate matter with an aerodynamic diameter less than or equal to 2.5 or 10 µm). Studies indicate that 70% of the smoke particles emitted by wildland fires are PM2.5 (Ottmar 2001). The most recent studies regarding the effects of particulate matter on human health indicate that PM2.5 are largely responsible for health effects including mortality, exacerbation of chronic disease, and increased hospital admissions.

The regulations that established visibility protection and set national goals also comes from the Clean Air Act, which strives for “the prevention of any future, and the remedying of any existing, impairment of visibility resulting from man-made air pollution.” Wildfires contribute to regional haze and visibility impairment, and thus covered by regional haze regulations.

While regional haze is considered a welfare issue, smoke can also reduce visibility to such low levels that it becomes a highway safety issue. Although smoke can present visibility problems anywhere in the country, highway safety is most at risk in southern states. This elevated risk is tied to the amount/frequency of prescribed fire in this region (roughly 6-8 million acres of southern forests are treated with prescribed fire each year, Wade et al. 2000), the generally humid climate, and the proximity of wildlands to population centers. This area is by far the largest acreage managed with prescribed fire in the country and fire treatment intervals are typically every 3 to 5 years. The combination of frequent fire and wildlands intermixed with homes and small towns crates an extensive and complex wildland-urban interface problem.

The potential link between smoke exposure of firefighters and impacted communities and related health effects is another growing concern. For instance, wildland fires subject firefighters to high enough smoke exposure to warrant occupational health concerns (see section above). At the community level, the relationships between smoke exposure and health effects are less certain, but given the large numbers of individuals exposed, are reasons for concern.

In addition to increasing regulation, public tolerance of smoke has diminished over time, and complaints are frequently received about smoke impacts from prescribed burning, wildland fire use fires, and wildfires. In some cases, lawsuits have affected regional prescribed burning programs.

Agencies considering management options for prescribed fire, wildland fire use, and even wildfire suppression routinely consider possible implications for and impacts from smoke. Smoke management is a process by which land managers can estimate the potential smoke impacts of a given fire. The process centers around answering two questions: how much smoke will be produced and where will the smoke go. Answering these questions involves estimating fuel loads, calculating fuel consumption and subsequent emissions, followed by determination of transport and diffusion of the smoke away from its source. The BlueSky Smoke Modeling Framework (Larkin et al. 2009) is one commonly used system designed to provide land managers with the ability to assess the potential smoke impacts of a wildland fire. The ability to predict smoke impacts enables managers to better quantify the potential consequences of their actions and communicate better information to regulators, local officials, and the public. Knowledge of smoke impacts can also allow managers to focus their tactics and fire management resources to control and minimize adverse effects from smoke.

Addressing questions such as these is accomplished by following a series of logical steps as outlined in O'Neill et al. (2009) that combine basic fire activity data such as fire size and location with atmospheric model data describing the full three- dimensional state of the atmosphere as it evolves over time. The result is an estimate of the ground level smoke concentration, typically in terms of PM2.5, that is both time and space dependent.

Conceptual Model

The conceptual model shown in Figure 16 provides a framework for assessing the impact of a set of strategic decisions relevant to wildland fire on values at risk due to smoke. These values, include regional haze, visibility hazards, and human health. Strategic decisions are choices available to land managers and others that may impact these values. These decisions fall into two general categories: those that impact smoke emissions and those that seek to mitigate smoke's impact.

The strategic decisions that impact smoke emissions include fire prevention efforts and fuels management programs. Fire prevention programs are direct efforts to reduce the number of unplanned, human-caused ignitions. While it may seem logical that any activity that reduces ignitions results in benefits for values at risk from smoke, the absence of fire or some other fuel treatment can lead to a larger impact at some future time when a natural ignition occurs.

Fuels management is the second strategic decision that impacts smoke emissions. As discussed above, managing the accumulation of fuels reduces the potential fire intensity and reduces the amount of smoke released by a fire. Using fire for fuels management requires making trade-offs between relatively frequent prescribed fires (every 3-5 years for southern forests) that release relatively small amounts of smoke versus an unplanned wildfire which depending on time since last burn could release significantly larger amounts of smoke in a single event.

The second group of strategic decisions are those that seek to mitigate the impact of smoke on the values at risk. These include communication, smoke outreach and air quality regulations, which seek to modify public behavior and perceptions in a way that reduces impact on the values at risk. Communication seeks to mitigate smoke impacts by informing the public of possible hazards, either health or visibility hazards, with the intention of changing public behavior to reduce the smoke impact (e.g., spending less time outside, evacuation, not driving a certain route, etc.)

Although similar to communication, smoke outreach is directed more at changing the social acceptability of smoke, particularly from prescribed fires. By improving the social acceptability of smoke, it is hoped that smoke from fuels management activities would not be overly restricted by air quality regulations, the third strategic decision that seeks to mitigate smoke impacts.

When examining social acceptability one important aspect often overlooked is cultural expectations. Historic tribal management practices have employed fire and smoke as a management tool for millennia. Many tribes today wish to restore these important management practices and the benefits they provide. Traditional Ecological Knowledge provides a foundation on which to build research and monitoring efforts to re-achieve a societal system of intergenerational cumulative observation in a contemporary context. In order for many tribal practices to achieve multiple benefits, they need to be coordinated with specific ecological indicators, such as a specific point in the lunar cycle, the first drop of acorns, or a short dry period prior to incoming migrations of nesting songbirds. Understanding and implementing these practices, followed by effective demonstration and communication of societal benefits, could lead to broader public support of certain practices within and adjacent to affected communities..

Most of the remainder of the conceptual model deals with determining the smoke concentrations that impact the values at risk as a result of various strategic decisions. Smoke concentrations are a complex function of fuel, how it is burning (fire behavior), and the subsequent transport and dispersion of the resulting emissions. The transport and diffusion stage that adds considerable complexity to assessing smoke impacts. While some smoke impacts tend to be local such as visibility hazards and the most acute health impacts, smoke can have major impacts on the values at risk far away from the fire.

Predicting the smoke impacts of wildland fires requires knowledge of a range of processes. The first process is describing the emissions source in terms of both pollutants and heat release. The amount of fuel available to be consumed by a fire is a primary consideration in estimating the amount of smoke produced and also influences the chemical composition of the smoke through slight variations in emission factors for various compounds. Fire behavior is a function of fuels, weather and topography. Human actions can modify fire behavior, specifically prescribed fire. By altering the ignition plan for a prescribed fire, a burn boss can change the relative proportion of fuel consumed by head, flank and backing fires which directly alters the amount of smoke produced and heat release as each fire type differs in combustion efficiency.

The next process involves determination of plume rise through examination of the atmosphere's stability and wind profile as well as the fire-source rate of heat release. Again, fire behavior and human manipulation of fire behavior supply important information for determining plume rise. The third process, which overlaps with the plume rise process, is the actual movement of the smoke (transport and dispersion). During the rise and transport processes, pollutants may chemically react causing changes in the smoke composition. The final process relevant to assessing smoke impacts is deposition, or the removal of a pollutant from the transport process.

The ability to model potential smoke impacts across scales ranging from local to regional as well as global focuses on answering two questions: how much smoke is produced and where will that smoke go. The amount of smoke produced is determined by the amount and type of vegetation consumed by the fire as it moves across the landscape. Where the smoke goes is determined by the interaction of the smoke's buoyant rise with atmospheric flow patterns. Figure 17 shows the probability of smoke from a fire in Montana impacting other parts of the country. This map is based on the transport/dispersion resulting from 30 years of climatological conditions for one week in March. Incorporating both local (near-fire) and remote effects will require the development of a transfer function to get from the fire source region to the area of concern (sensitive receptor).

The last pieces of the conceptual model include knowledge of the ambient pollutant concentration along with the social acceptability of smoke. The ambient or background, pollutant concentration sets the baseline to which smoke's contribution will be added. The social acceptability component merges information regarding population density and demographics along with cultural expectations regarding fire on the landscape. Studies suggest that smoke does not appear to be a barrier to the use of prescribed fire for a majority of the population as the desire to improve forest health and/or reduce future fire risk tends to outweigh smoke concerns. However, for some segments of the population smoke is a major issue due to health concerns that needs to be considered.

Potential Data Sources

The conceptual model for smoke impacts overlaps in a number of places with the conceptual models of other sub-teams. Primary data areas shared with other sub-teams include those related to basic fire behavior (fuels, weather/climate and topography), ignitions and to some degree information regarding health impacts. The data areas that need to be specifically developed for assessing smoke impacts include smoke concentrations, ambient pollutant concentrations, and ancillary data required to translate the smoke concentration values into health and visibility hazard impacts.

One of the largest data needs is a method to identify the connection between a potential fire's nominal location and where it's remote smoke effects are likely to be. If a potential fire's timing is known, this can be modeled using smoke trajectory and/or dispersion models. When a fire's timing is uncertain, climatological patterns can be utilized to identify the likely overall transport and dispersal of the smoke downwind. With at least some knowledge of when during the year the fire is likely to occur (e.g. knowing the climatological peak of the fire season), such an approach can help winnow down where the smoke effects are likely to be felt based on the historic prevailing wind patterns during this portion of the year.

We propose utilizing transfer functions, one for each climatological month, to quantitatively describe the connection between the fire's location and the potential for remote smoke effects. Doing so allows the values at risk remotely to be linked back to the fire location for analysis within the cohesive strategy framework. Using the North American Regional Reanalysis for the period 1979-2008 and the HYSPLIT trajectory model, the USFS PNW AirFire Team has utilized a record of 107 smoke trajectories to identify how often during each climatological month the trajectories from a given location reach any other CONUS location. To accomplish this trajectories were released every six hours from every NARR grid cell (32-km resolution) for the 30 year period. Counts were then done to identify the percentage of trajectories from a given source location reaching a given remote location in a given analysis period (in this case per climatological month). The time required to reach the remote location is also tallied. The analysis is available for fire locations across CONUS. While this methodology can provide a simple and quick probabilistic approach to making the needed scale connection for identifying smoke impact risks, significant challenges remain, relating to knowing the plume injection height of the fire, and translating simple metrics of trajectories into the relative potential for smoke concentrations. Other issues include the sensitivity of the results to interannual and inter-month variability. These issues will need to be addressed more fully as the analysis continues.

For specific areas of special fire risk concern, an analogous, but more computationally expensive approach is available where a sample fire from that period is run through a full smoke dispersion model, such as CALPUFF or the HYSPLIT dispersion component. By running the fire for all possible starting days within a specific period of interest (e.g. every July day of the past 30 years), a probabilistic impact can be determined that reflects the overall climatological meteorological patterns as above, but with better ability to identify specific smoke ground concentration probabilities. This process is available through the USFS PNW AirFire AQUIPT system (http://aquipt.airfire.org), but as it takes 24-hours to process a single fire, its use must be targeted. One potential use is to process enough sample fires through AQUIPT to calibrate the faster trajectory approach described above.

Ambient pollution concentrations is another difficult topic. While observations of pollutant concentrations are readily available through the EPA's airnow web site (http://www.airnow.gov), these observations already include smoke in their measurement. Therefore these ambient pollutant values are not directly used in assessing any direct pollutant impact as this could lead to double counting smoke's impact. The role of ambient pollutants occurs as a factor in determining the social acceptability of smoke and how that feeds into air quality regulations and fuels management. Areas with high ambient pollutant concentrations generally have less tolerance of smoke due to the potential adverse consequences of violating the NAAQS.

The remaining data required for assessing health and visibility hazards are generally available from the census as they include population density and demographic information. Visibility hazard assessment requires information on road network density, easily determined from available GIS road layers which are readily available.

EXPECTATIONS FOR PHASE III

The NSAT roles in Phase III will be primarily to develop analytical models, interact with the regional strategy committees and workgroups to interpret the goals, objectives, and actions proposed in their respective Phase II reports, explore management options for each region, and interact with all Cohesive Strategy committees on potential outcomes associated with identified management options. These efforts will include:

1. Translate conceptual models developed in Phase II into quantitative models, as appropriate.
2. Compile and integrate appropriate data needed to quantify and validate the relationships presented in the models.
3. Identify performance measures that can be used across all regions and within a given region.
4. Identify geographic variations in the quantitative models to reflect appropriate differences across the regions.
5. Interact with the RSCs and WGs to validate that the modeled relationships are reasonable.
6. Explore potential management options across the regions that reflect the decision space available for broad national and regional choices related to wildland fire management and policies.
7. Interact with the regional committees to iteratively identify and refine regional strategies to include in the comparative risk assessment – national tradeoff analysis.
8. Conduct and document the comparative risk analyses – national tradeoff analysis. Coordinate efforts with other committees to report on results of the national tradeoff analysis.

Each of these steps is briefly described below.

1. Translate Conceptual Models

During Phase II NSAT sub-teams developed conceptual models related to specific topics. Each topic is relevant to understanding potential consequences or outcomes associated with wildland fire management. The individual conceptual models describe potential information needed to model from inputs and drivers to potential outcomes and consequences. In many instances the desired data to drive the individual models overlap with information needed by other models. The challenge in Phase III will be threefold: first, integrate the individual conceptual models into an analytical framework that retains the essential elements of each model; second, remove redundant relationships without sacrificing accuracy; and third, simplify the resulting models to rely on available, derived, or estimated data for use in the current analytical cycle.

The expected outcome is likely to be a nationally consistent set of analytical models that can operate at regional scales using regionally specific data, relationships, and assumptions. This should allow a consistent analysis across the nation while retaining the individuality of the regions and recognizing regional differences.

2. Compile and Integrate Appropriate Data

The specific data, relationships, and information needed to run the analytical models will be brought together for initial tests. This testing process will validate that information is available for the analyses and that the models can consistently and accurately translate the inputs into outputs and outcomes.

3. Identify Performance Measures

While each of the RSCs and WGs have proposed performance measures, a challenge facing NSAT is to determine to what extent these and other performance measures can be modeled for comparison within the comparative risk assessment. The starting place will be to attempt to deliver the performance measures proposed in Phase II and Phase I. To the extent possible the analytical models will be designed to provide these measures or surrogates of these measures. Additional performance measures will be explored to help explain potential consequences of differing wildland fire management options and the underlying relationships between inputs, drivers, and outcomes.

4. Identify Geographic Variations

Variations in wildland fire and wildland fire management across the major regions of the country are readily apparent. It is important that the analytical models reflect appropriate variations so that reasonable and useful results can be brought forward for consideration. To some extent, the available data will drive the variations appropriately and regionally specific model parameters will be capable of capturing the variations of importance. It is possible that some variation in the models themselves will be necessary to capture the regional differences and regionally specific performance measures of interest.

5. Validate Modeled Relationships - Interact with RSCs and WGs

It is important validate that the analytical models, coupled with available information, yield reasonable results and performance measures. Through interactions with the RSCs and WGs this validation step will include explanations of relationships among potential actions/objectives and outcomes/drivers. The intent is to gain understanding of the models among the RSCs and WGs so that the resulting models will deliver reasonable results useful in making decisions regarding regional and national wildland fire management strategies.

6. Explore Potential Management Options

In Phase II each region has described a minimal set of management options or scenarios they feel would be useful in understanding potential consequences or outcomes from the various objectives and actions in their Phase II reports. The intent of this step is to use these minimal sets of management options coupled with additional options to explore the potential decision space nationally and regionally. It is likely that certain options will be generally unappealing, but it may be important to understand how outcomes might vary across a wide spectrum of potential inputs. For instance, while few land managers are likely to be interested in curtailing prescribed fire programs, it will be very helpful to understand what outcomes are likely to happen under such a scenario. Likewise, it may not seem reasonable to assume that large increases in fuel treatments would be funded, but it will be very helpful to understand how much of an increase in fuel treatment will be needed to achieve a substantial reduction in wildfire risk. This stage is characterized with the term "explore" partly because there is no way to predict ahead of time what boundaries make sense to explore. The regions have provided a beginning minimal set of management options or scenarios. As a minimum these will be explored to the extent possible.

7. Interact with Cohesive Strategy Teams to Refine the Regional Strategies

This step is designed to allow interaction among the various Cohesive Strategy committees to gain understanding of the linkages among management options and potential consequences of actions and objectives. During this interaction, the regional strategies will be refined and narrowed as appropriate to the set of management options desired to include in the comparative risk assessment – national tradeoff analysis. While not resulting in a "preferred alternative" for each region, it is expected that the decision space will be narrowed to a smaller set of options that are practical and reasonable for each region.

8. Conduct the Comparative Risk Analysis – National Tradeoff Analysis

Given the refined and narrowed set of management options for each region, the analytical models will be used to project potential outcomes and consequences within each region and summarized nationally. The intent is to show the tradeoffs associated with management options. Tradeoffs will reflect how risk varies under each management option – thus, the inputs assumed for each management option and the projected outcomes/consequences are summarized at the regional and national level. The intent of the tradeoff analysis is not to make a final decision as to which management option will be selected for each region. Rather the intent is to derive information useful for further deliberations among stakeholders, partners, agencies, and policy makers as decision processes move forward. Some proposed actions within the regional strategies may be adopted for implementation without further deliberation – for instance, those actions requiring no new funding or policies and that have broad acceptance by partners and stakeholders. For some actions and objectives the Cohesive Strategy may be seen as providing a deliberative process involving transitions that require considerable discussion and debate. For these actions and objectives it may be appropriate to reveal the potential tradeoffs and initiate the discussion and debate rather than "decide" immediately. The NSAT report of the national tradeoff analysis is expected to consist of the description of the underlying models, data, assumptions, and relationships presented in the models as well as tables and graphics displaying and describing the tradeoffs associated with the regional and national management options.

CONCLUSIONS

In many ways the products from the subteam efforts reflect the state of knowledge about various aspects of wildland fire and the availability of existing models and data. Several trends are evident.

1. Fine-scale processes tend to be better understood than broad-scale processes or strategic issues. For example, there is an extensive literature on fire behavior and combustible properties of fuels; less is understood about the large-scale effectiveness of strategic fuel treatments.
2. There has been considerably more research focused on the biophysical aspects of wildland fire than has been directed at equally important socio-political issues. Thus we can assuredly state that fire-wise landscaping and construction materials will help reduce the incidence of homes lost to wildfire; we are less confident as to how to ensure such practices are implemented. Smoke is an archetypal issue—technically well-understood but socio-politically complex and difficult.
3. Integrated research efforts that focus on interactions among human and physical factors are becoming more common and are highly promising. For example, there is a growing body of research into how socioeconomic, educational, regulatory and enforcement factors relate to wildfire ignition processes.
4. Data from Federal agencies is decidedly more complete and accessible than from other entities. Such inconsistencies can lead to inaccurate conclusions if the limitations of the data are not understood.

Each subteam has produced one or more conceptual model of the processes operating within their area of interest. Collectively, these conceptual models create a rich tapestry that illustrates the extensiveness, complexity and interconnectedness of wildland fire. Along with the information summarized on existing analytical models and data sources, the conceptual models provide a strong foundation for building more rigorous models in Phase III that can be used to compare and contrast alternative strategies for reducing risk.

Moving forward and building models that can provide quantitative estimates of risk to social values will not be easy. Each of the subteams identified limitations in available data and understanding that will pose challenges to overcome. Conversely, there is an extensive scientific literature covering the range of issues described here and multiple data sets that can be constructively applied. Some of the more information-limited issues are also the most important from a policy perspective, namely, strategic fuel treatments, large fire suppression effectiveness and costs, and public safety impacts of smoke. Our understanding of the social aspects of wildland fire management and potential impacts on communities is more advanced than generally recognized, but still far from complete and severely hampered by the lack of quantitative data. All of the aforementioned limitations notwithstanding, the general consensus of the NSAT is that we can provide substantive and meaningful information to help inform decisions at the conclusion of Phase III.

Finally, it is worth remembering that the work of the NSAT does not occur in isolation. All of the governing committees and advisory groups within the Cohesive Strategy have a continuing role in ensuring that the analyses are matched to the questions most important to the nation, utilize the best available understanding and data, and provide results that can be understood by all. Only then will the results from Phase III analyses be truly relevant and helpful.

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Table1. Fire causes, reported average annual ignitions, reported average annual area burned, and percentage shares of fires by causes, Department of Interior (DOI) and USDA Forest Service (USFS) (Jan 2000-Dec 2008) combined.

Cause	Average Annual Ignitions Reported	Average Annual Area Burned Reported, Acres	Percentage Share of Reported Ignitions	Percentage Share of Reported Area Burned
Natural/Lightning	10,874	5,496,235	45.34	79.90
Campfire	1,964	179,338	8.19	2.61
Smoking	418	22,387	1.74	0.33
Fire Use/Debris Burning	1,538	100,971	6.41	1.47
Incendiary/Arson	2,969	268,962	12.38	3.91
Equipment (Use)	1,338	246,804	5.58	3.59
Railroad	117	14,193	0.49	0.21
Juveniles/Children[1]	1,063	20,464	4.43	0.30
Miscellaneous and unknown[2]	3,704	529,313	15.44	7.69

[1] Classification of wildfire starts as Children require that the child be 12 years of age or younger (National Wildfire Coordinating Group 2005, p. 83); we assume that the same applies to the DOI General Cause of Juveniles

[2] The USFS Statistical Cause of Miscellaneous includes fires of unknown origin, and we have added to these wildfires without valid Statistical Cause codes entered into the National Interagency Fire Management Integrated Database (2011); similarly, DOI wildfire records without a valid General Cause were added to the miscellaneous category.

Sources: DOI General Causes are from National Wildfire Coordinating Group (1998, p. 17); USFS Statistical Causes are from USDA Forest Service (1995). DOI wildfire data are from the Wildland Fire Management Information database (National Interagency Fire Center 2011) and the United States Fish and Wildlife Service (2011). USFS wildfire data are from the National Interagency Fire Management Integrated Database (2011).

Table 2 Pathways to reducing firefighter deaths and injuries and associated strategic investments.

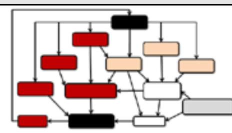
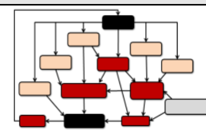
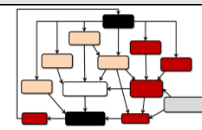
Strategic investment	Workforce emphasis	Incident management emphasis	Fire attribute emphasis
Position within Figure 2 shown by black and red:			
Standards, training, experience	X	X	
Technology, equipment	X	X	
Communications	X	X	
Health monitoring	X		
Personnel standards, screening efforts	X		
Incident learning	X	X	X
Fire behavior and weather modeling	X	X	X
Wildfire prevention efforts			X
Fuels reduction			X
Forest and disease management			X

Figure 1. Schematic diagram of the four principal steps within the CRAFT process and the engagement of various actors within each step. The weight of the blue arrows between actors (analysts & scientists, or managers & stakeholders) and each step corresponds to the degree of engagement with and responsibility for each step.

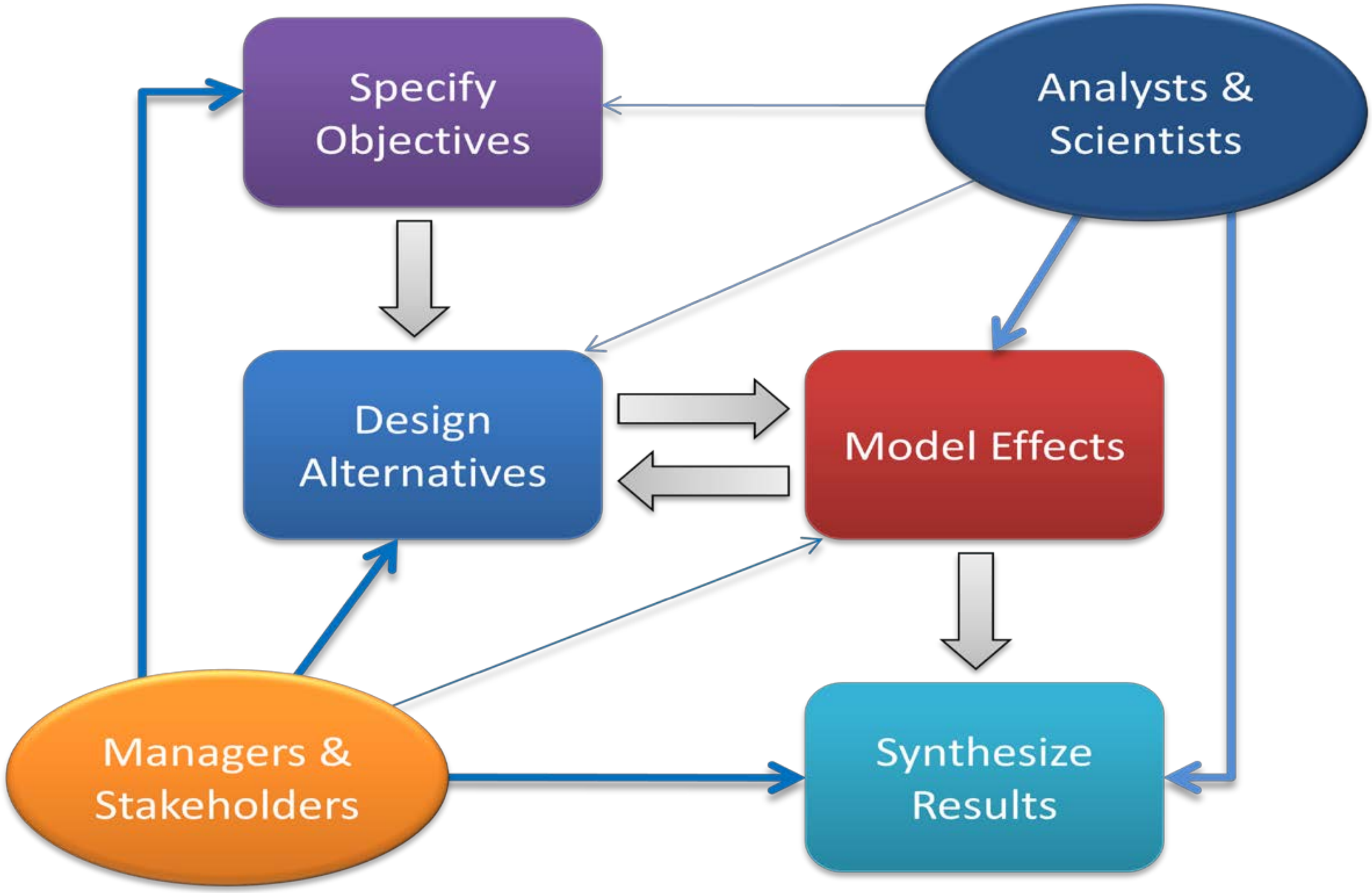


Figure 2. Simple conceptual model of the major anthropogenic factors involved in wildland fire management, principal interacting processes, and values affected by fire.

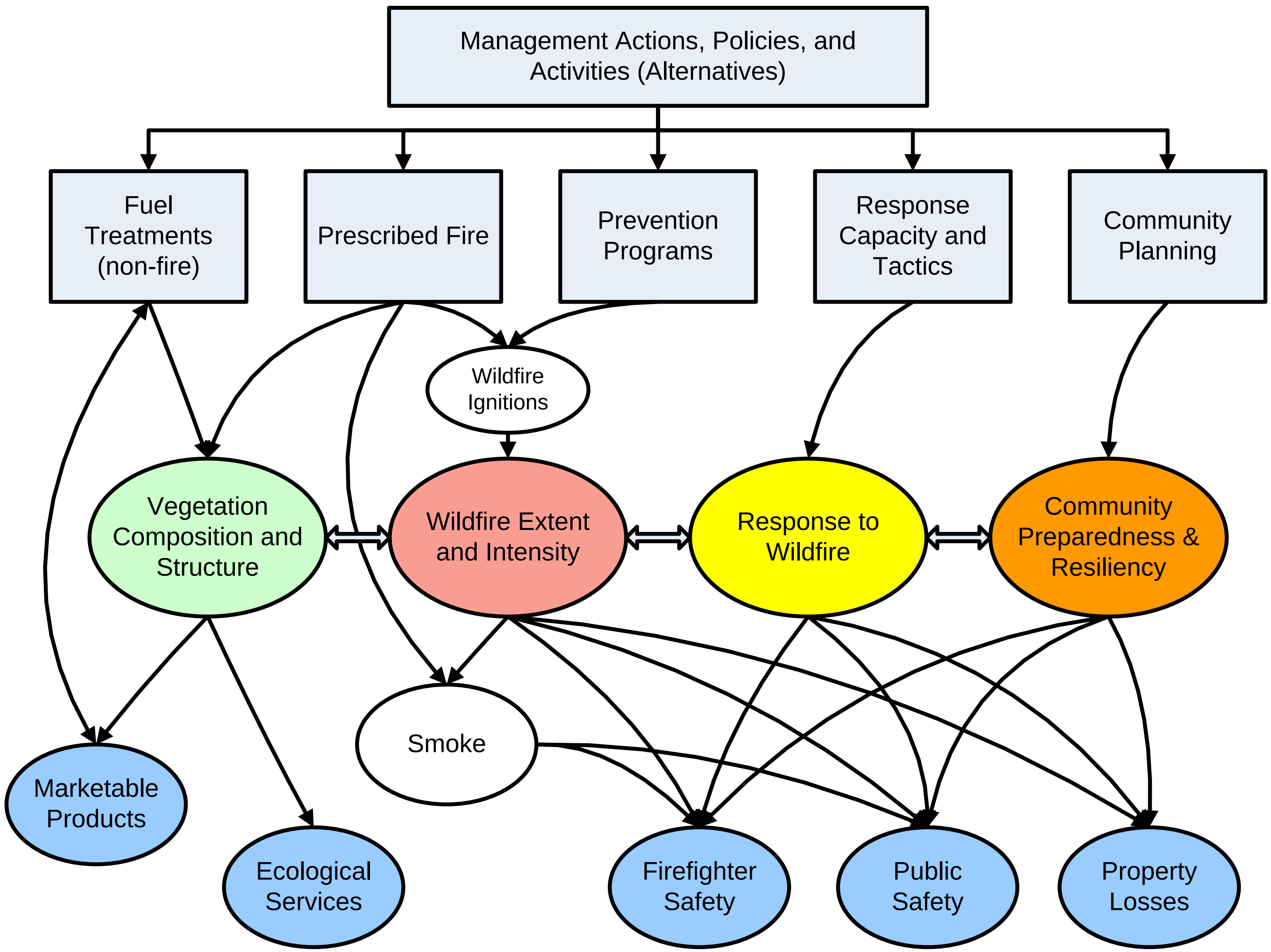


Figure 3. Conceptual model of wildfire ignitions and prevention

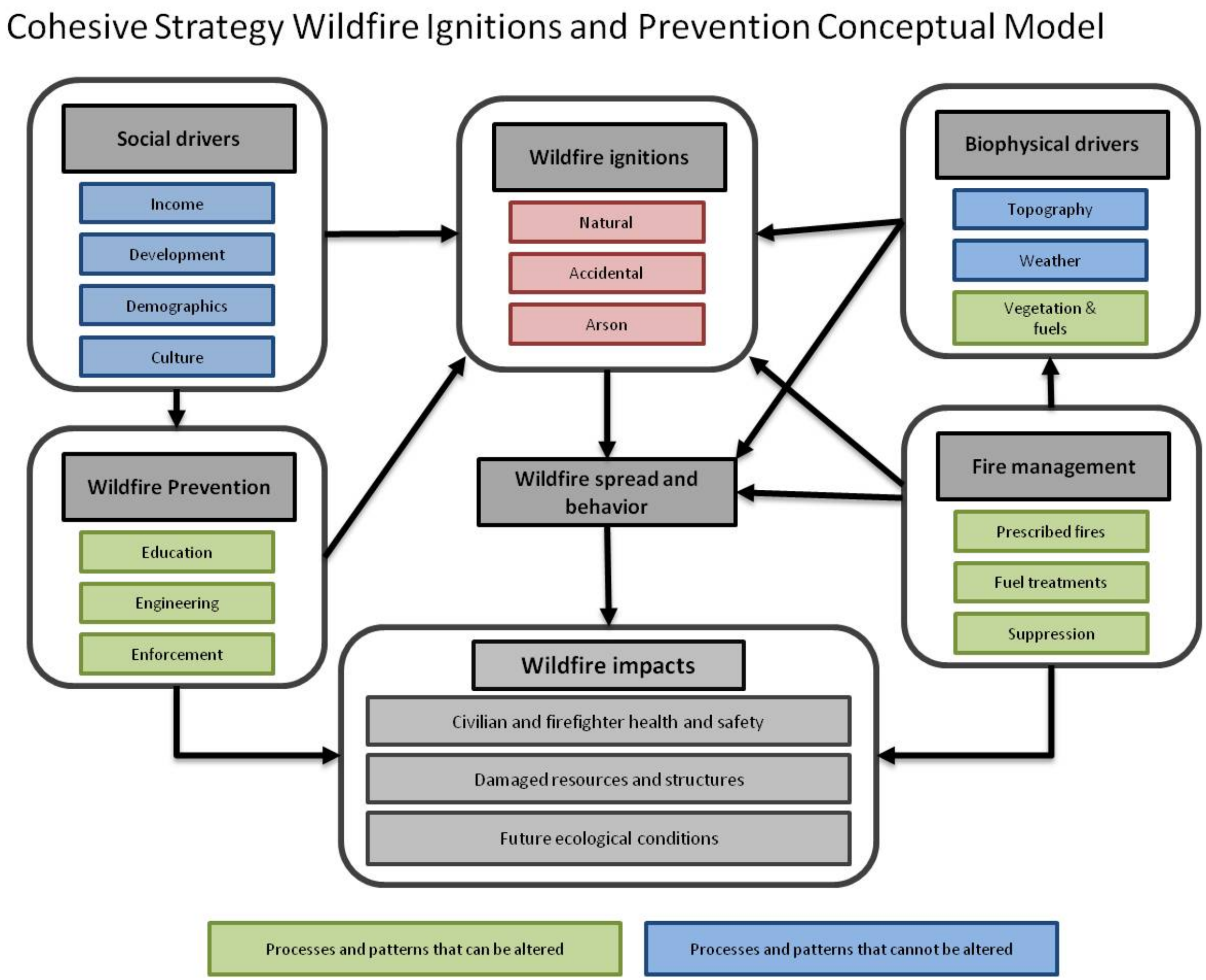


Figure 4. "Big Picture" Conceptual Model of Fuels Management

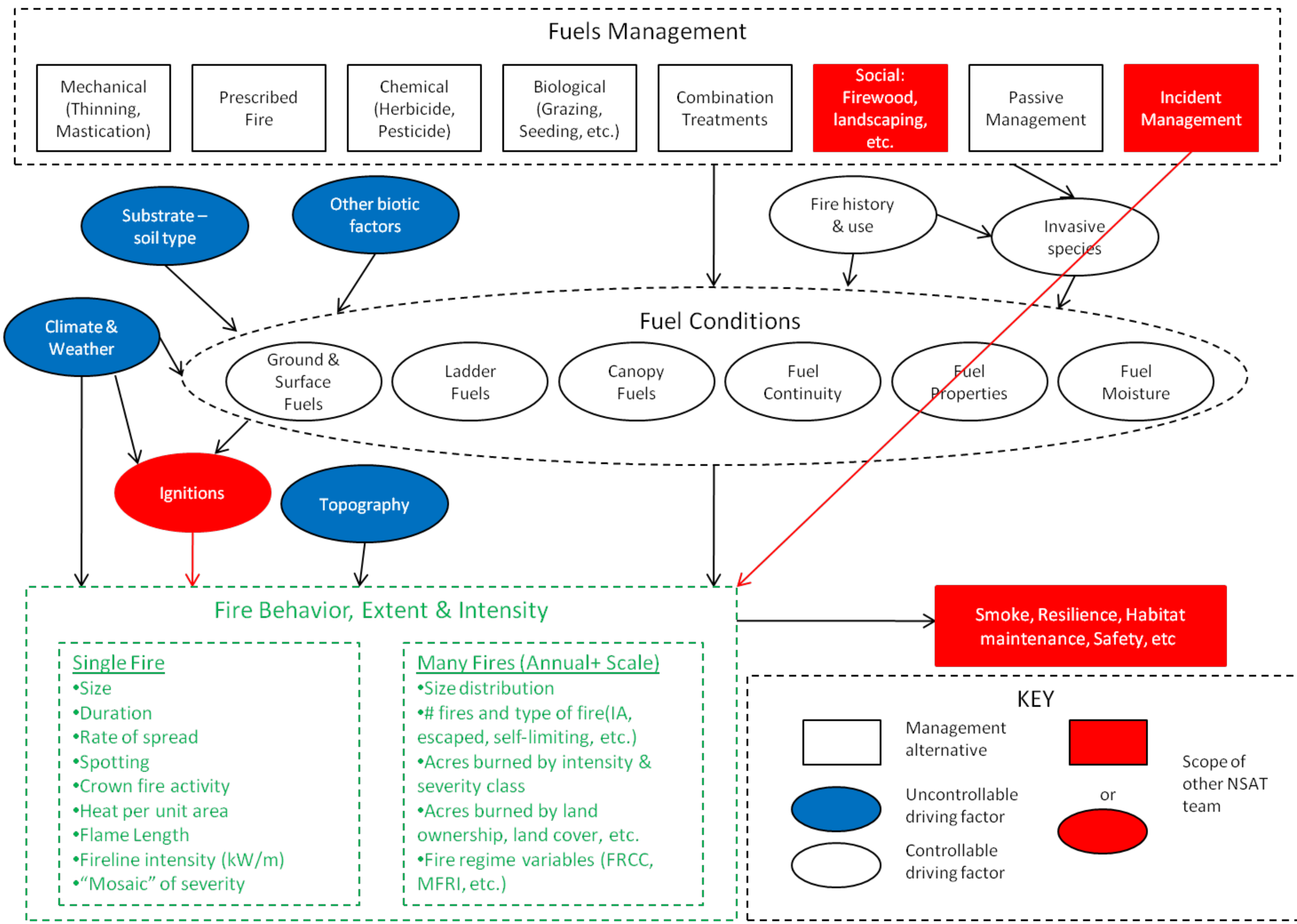


Figure 5. Conceptual workflow for fuel treatment planning process (modified from Funk et al. 2009)

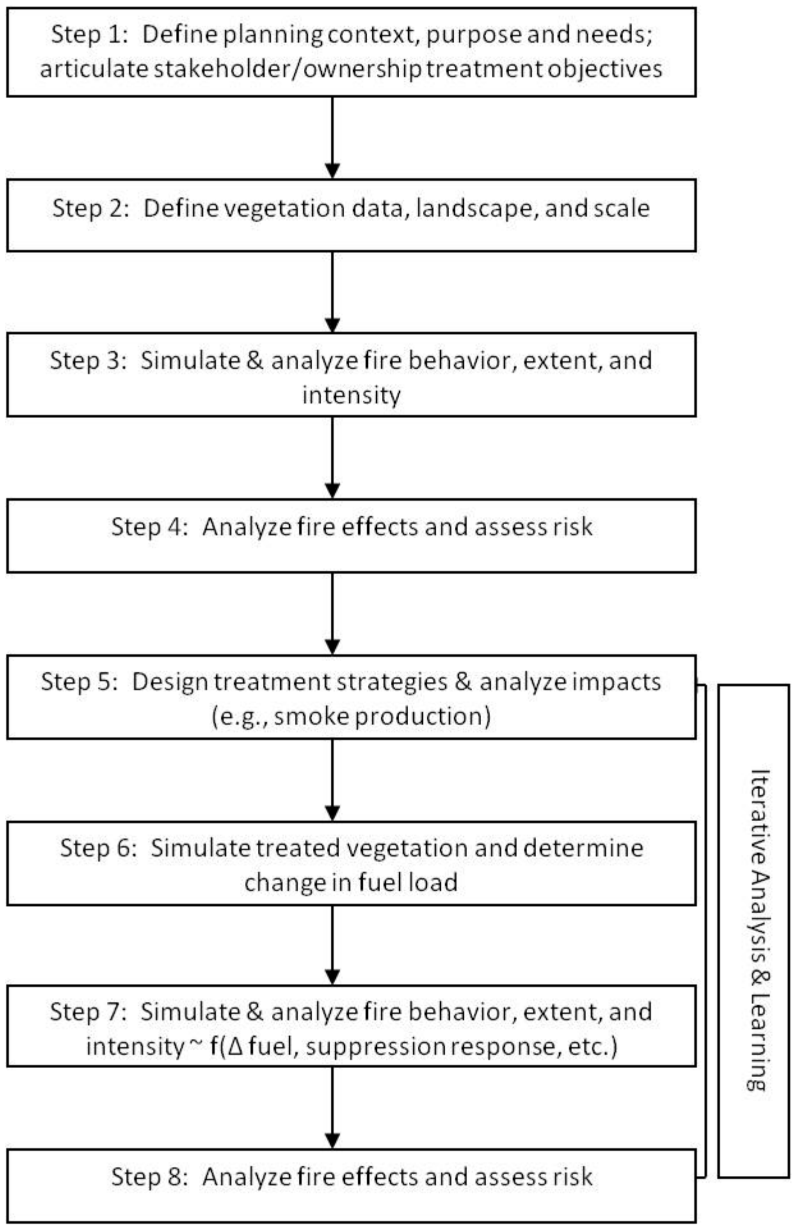


Figure 6 Combining risk analysis with management opportunity and ecological conditions with respect to fire determines coordinated landscape fuel treatment strategies. Blue rectangles indicate the overall analysis component (e.g.,, the spatial pattern of values, estimated fire behavior, and resource response jointly influence risk analysis, which in turn influences the mitigation strategy). Green rectangles describe/define the respective analysis components, and orange rectangles correspond to attributes descriptive of the particular analysis component (e.g., estimated fire behavior can be characterized by burn probability, flame length, and fire size). (Credit: Nicole Vaillant & Alan Ager).

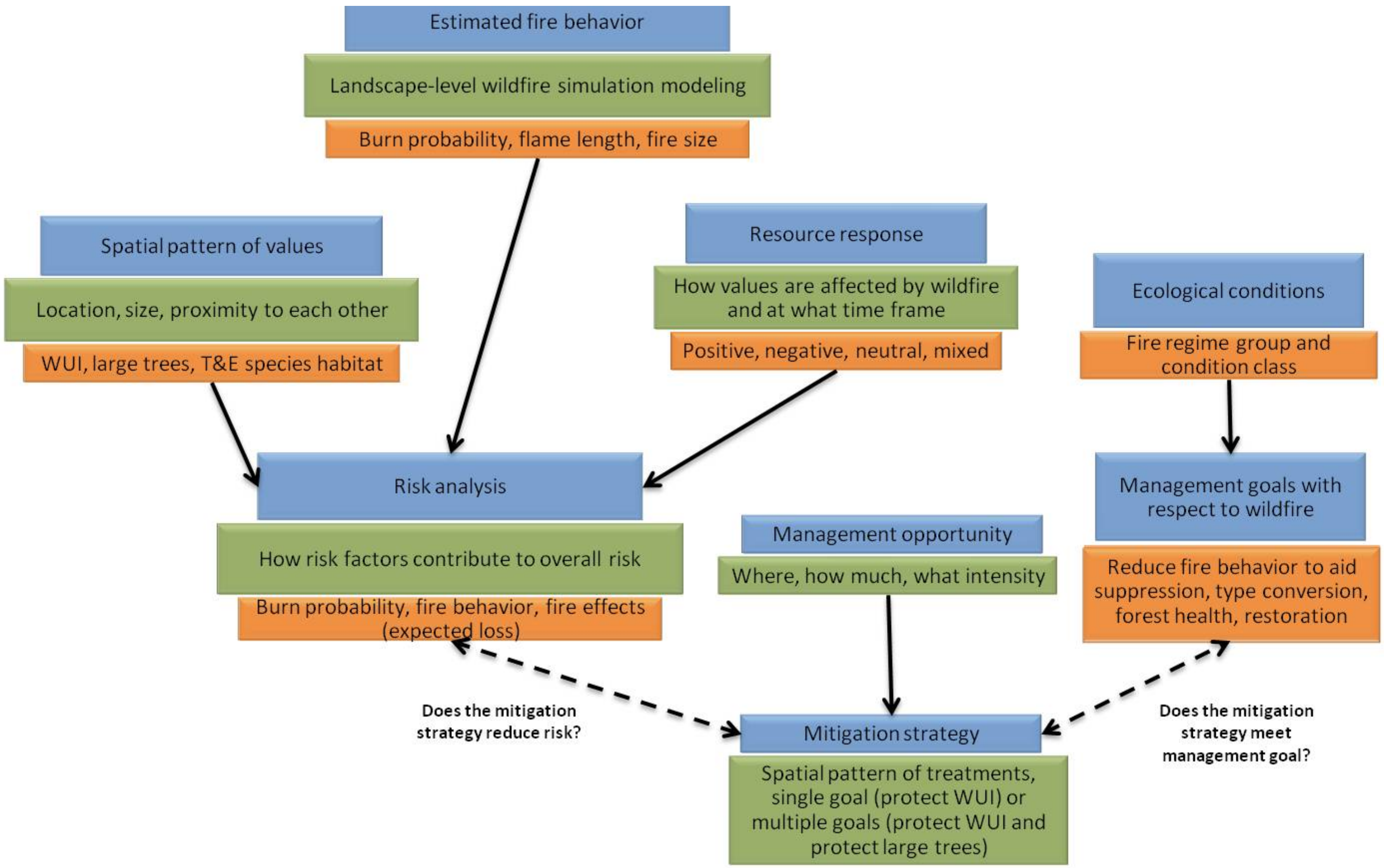


Figure 7. Strategic fuel treatment taxonomy, with illustrative examples of optimally placed treatments given variable motivation, fire regime, spatial pattern of values, and ultimate treatment strategy/system (Credit: Alan Ager and Nicole Vaillant)

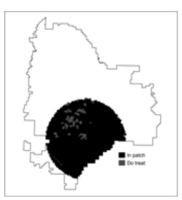
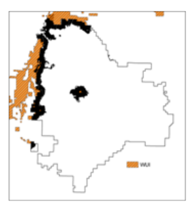
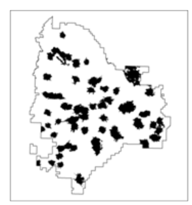
Motivation	Restoration	Protection	Protection	Protection	Restoration	Protection
Fire regime	Low severity (+ fire)	Mixed severity (+/- fire)	Mixed severity (+/- fire)	High severity (- fire)	High severity (- fire)	High severity (- fire)
Pattern of values	Dispersed (large trees)	Dispersed and prevalent (low density WUI, T&E)	One clump	Clumpy	Any	Low or none
Treatment Strategy	Create large contiguous areas of low hazard (minimum treatment for maximum area)	Strategic (SPLATs/SPOTs)	Localized protection (targeted treatments)	Localized protection (targeted treatments)	Restore natural fire barriers	Defensible fuel breaks along roads and other barriers
Treatment system	Low hazard fire containers	Treatment optimization model (FlamMap; TOM)	Defensible fuel breaks	Defensible fuel breaks	Strategic restoration	High hazard fire containers
Spatial treatment pattern						

Figure 8. Conceptual model of wildfire response and suppression.

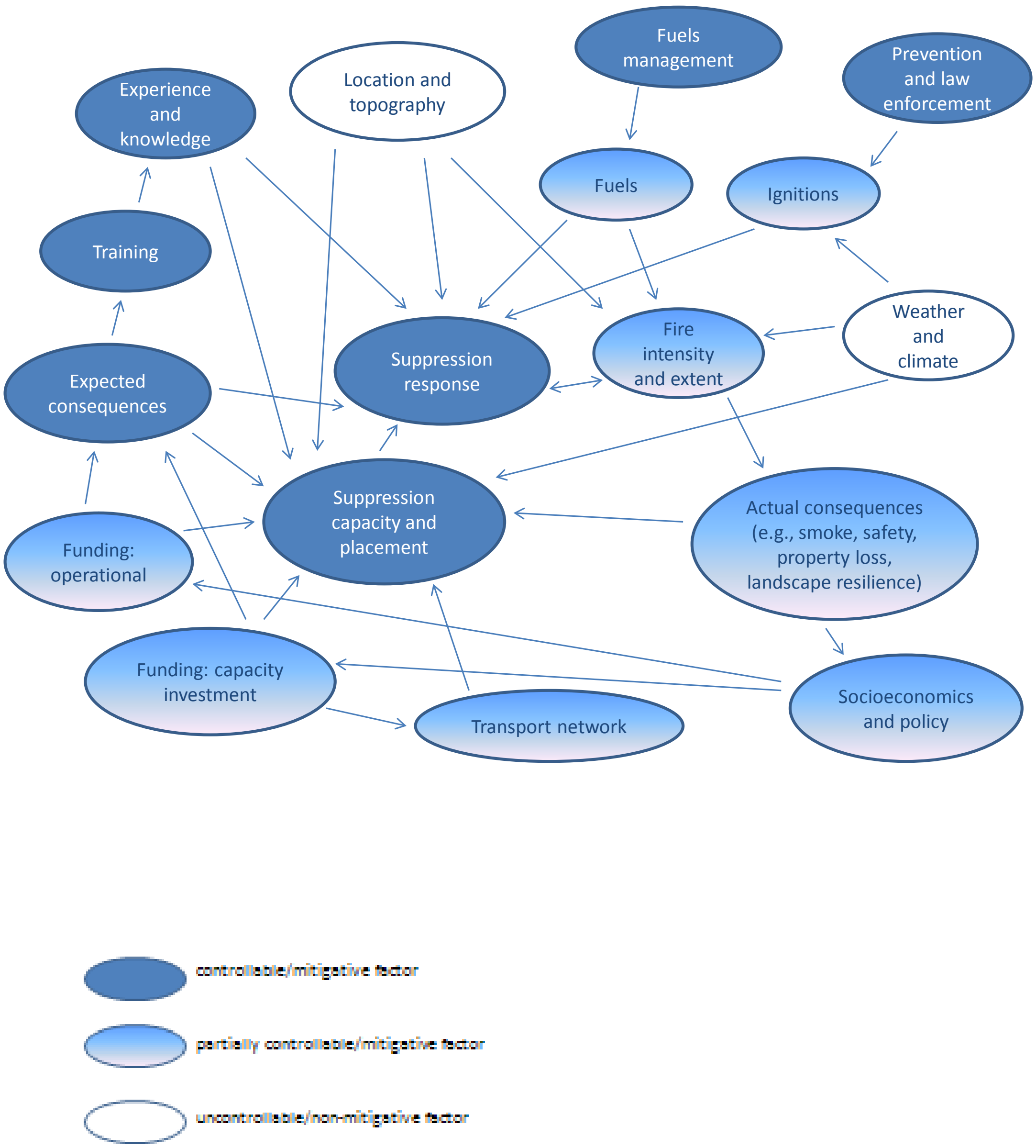


Figure 9. An overview of the composition and goals of a fire adapted human community.

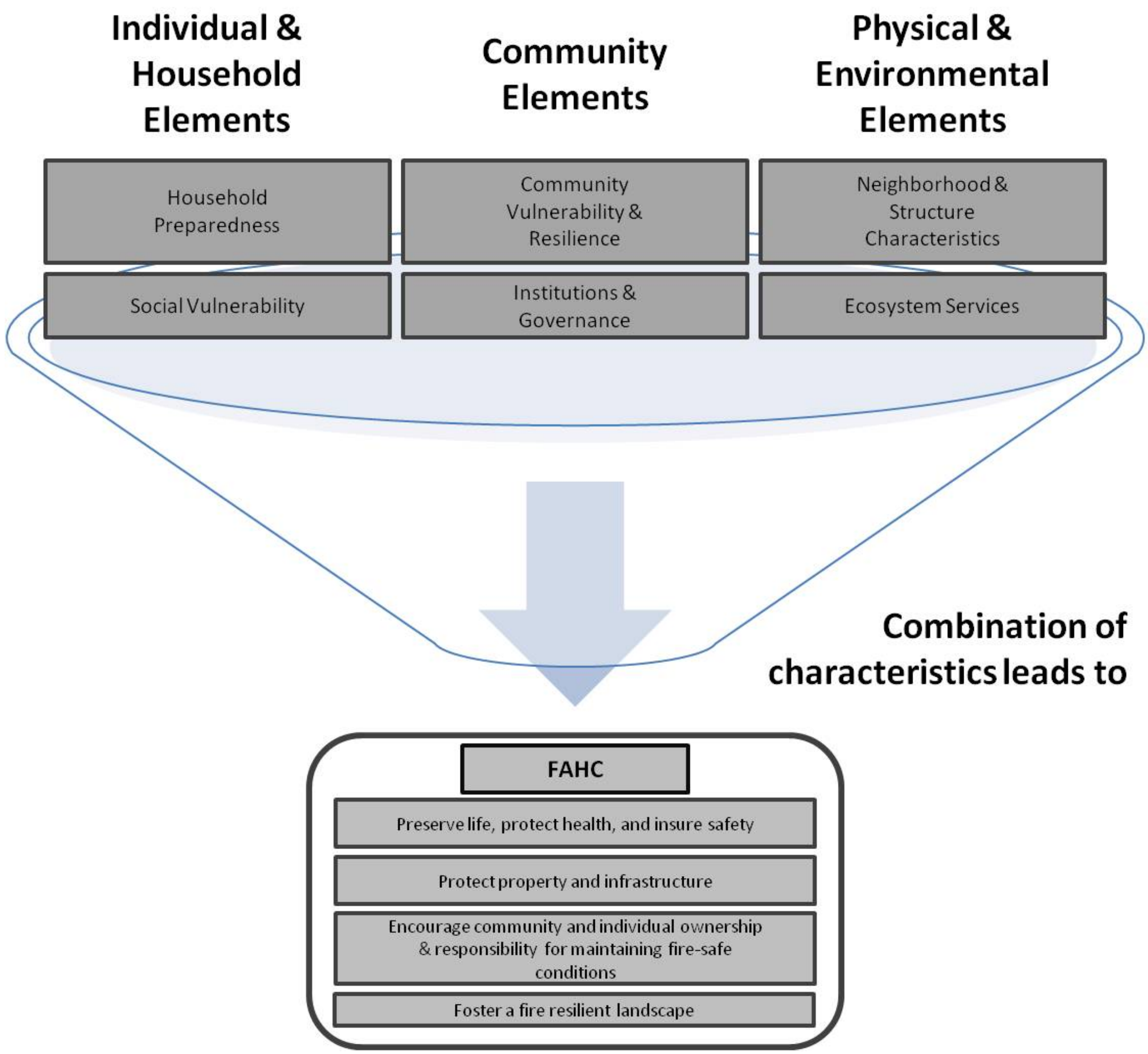


Figure 10. FAHC conceptual model of actions by wildfire timeframe.

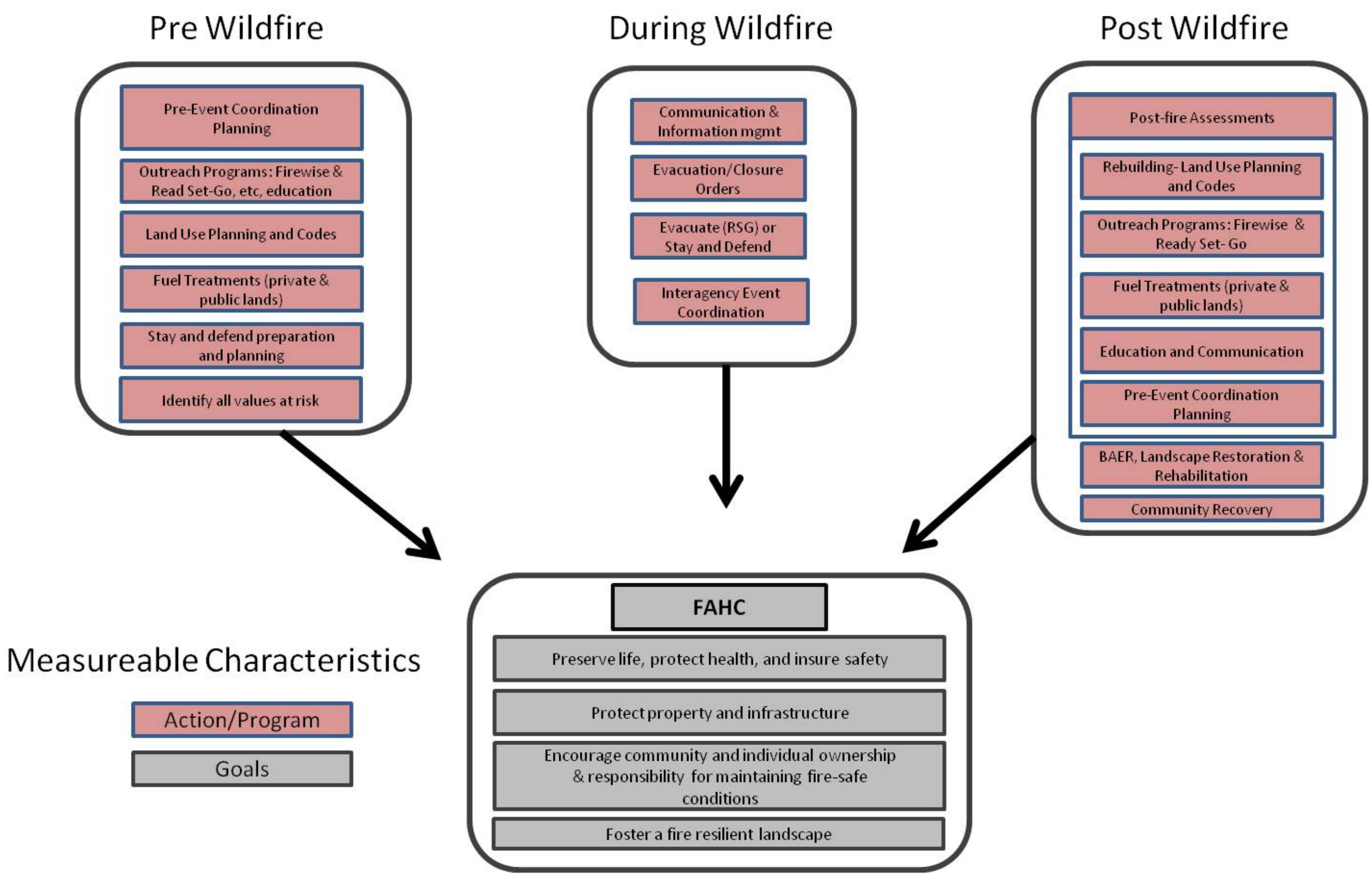


Figure 11. Conceptual model diagram for pre and post wildfire FAHC.

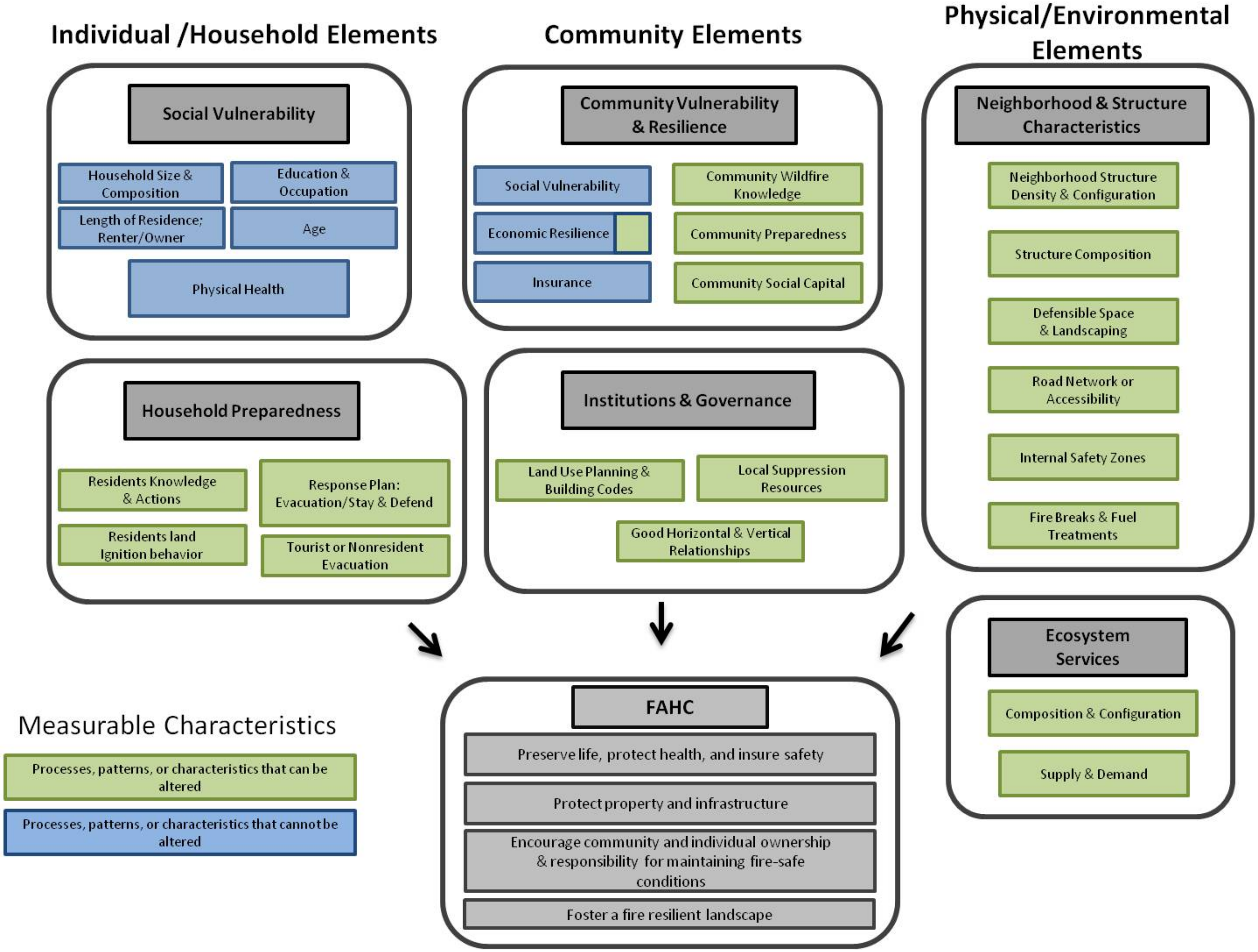


Figure 12. Conceptual model for during wildfire FAHC

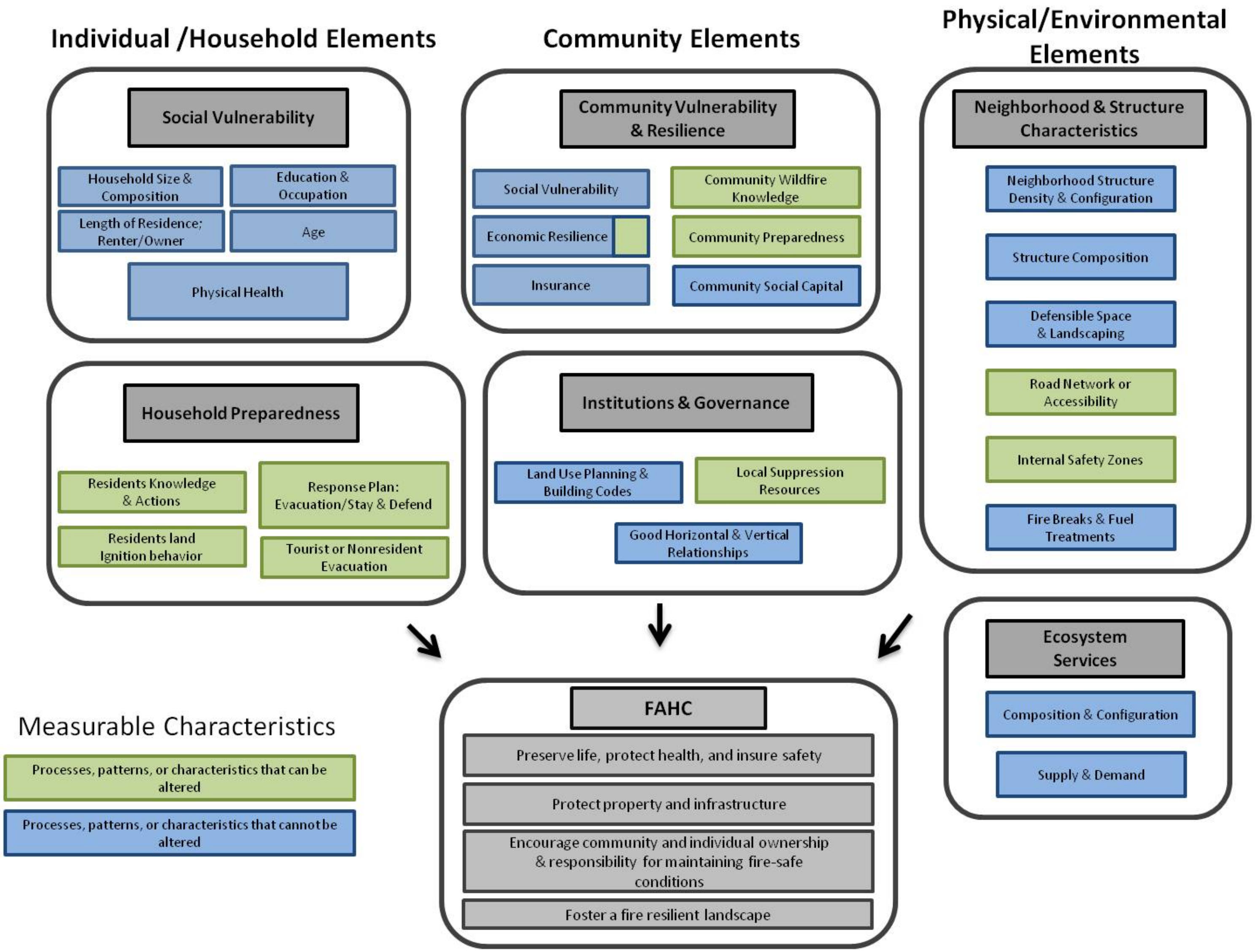


Figure 1 Cause of death for wildland firefighters 2000-2009 for all jurisdictions by the Cohesive Strategy Region in which the fatality occurred. Categories have been reclassified from the National Fire Administration's Fallen Firefighters Database based on incident descriptions.

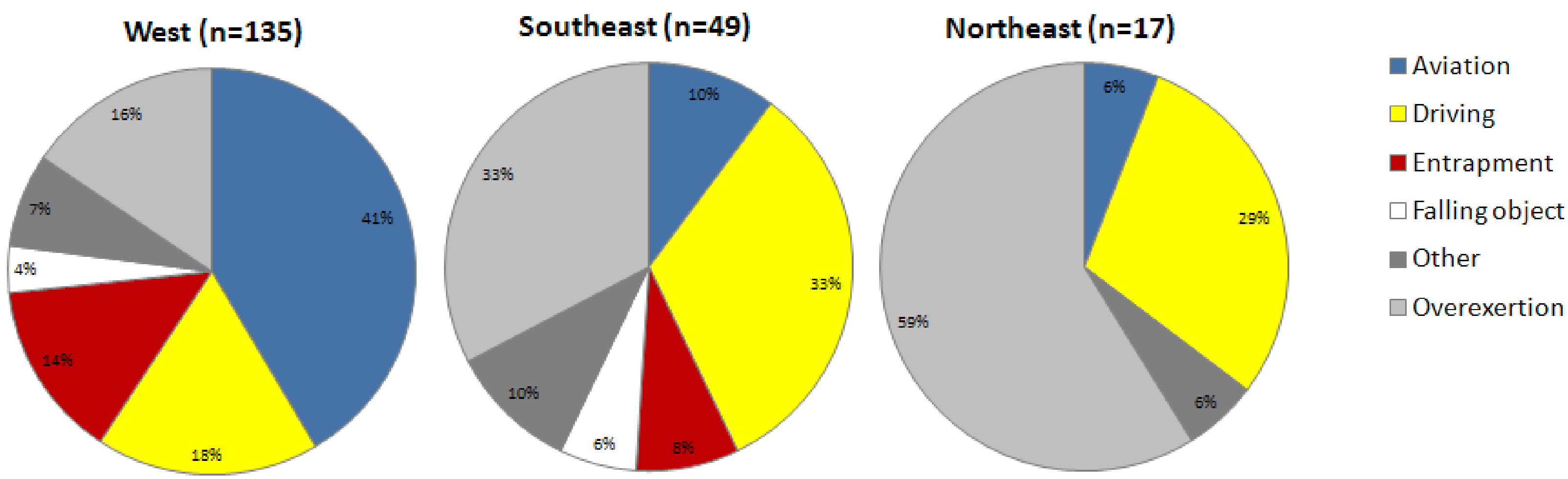


Figure 14. An integrated conceptual model for firefighter safety related to incidents.

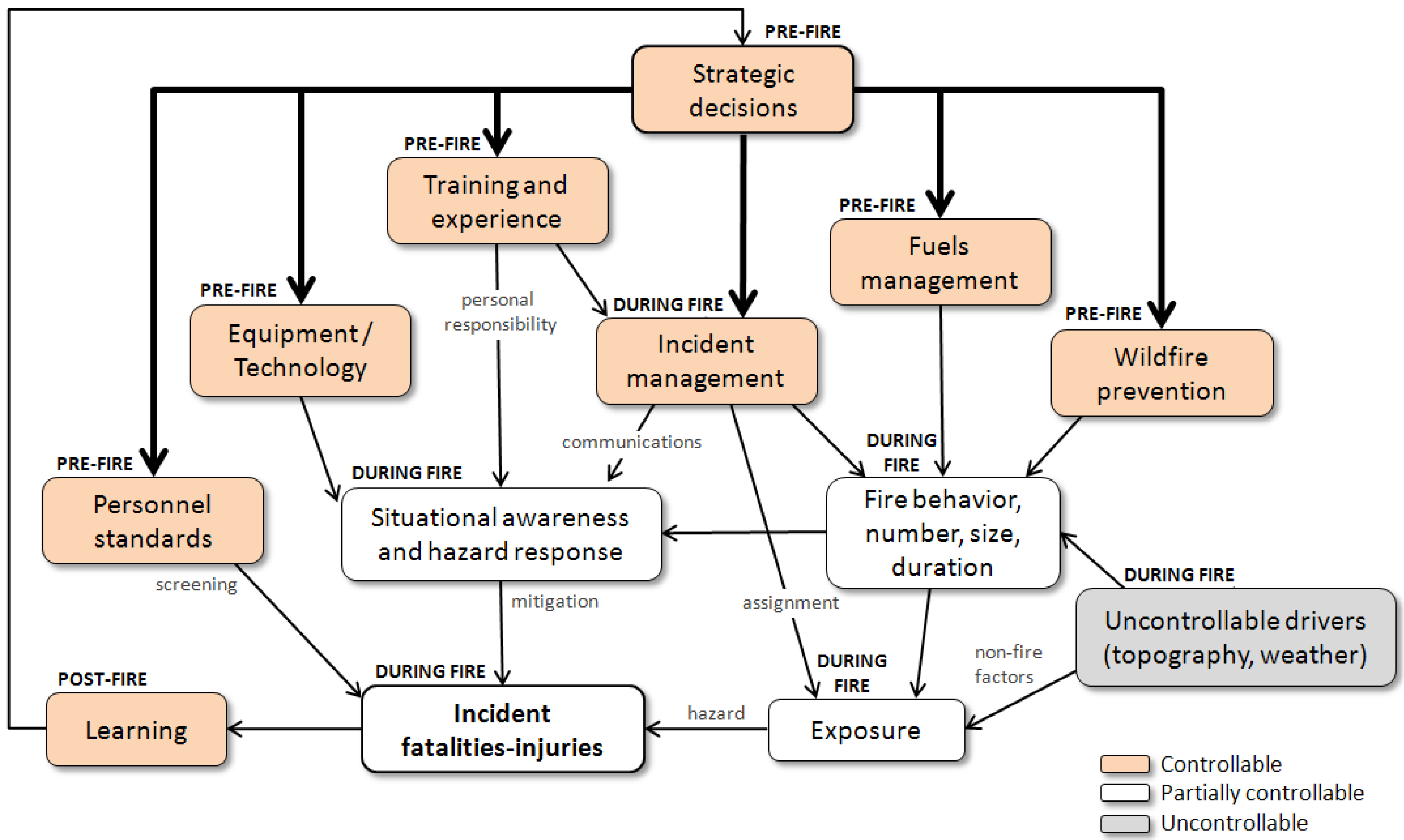


Figure 15. A conceptual model for long-term fire-fighter health.

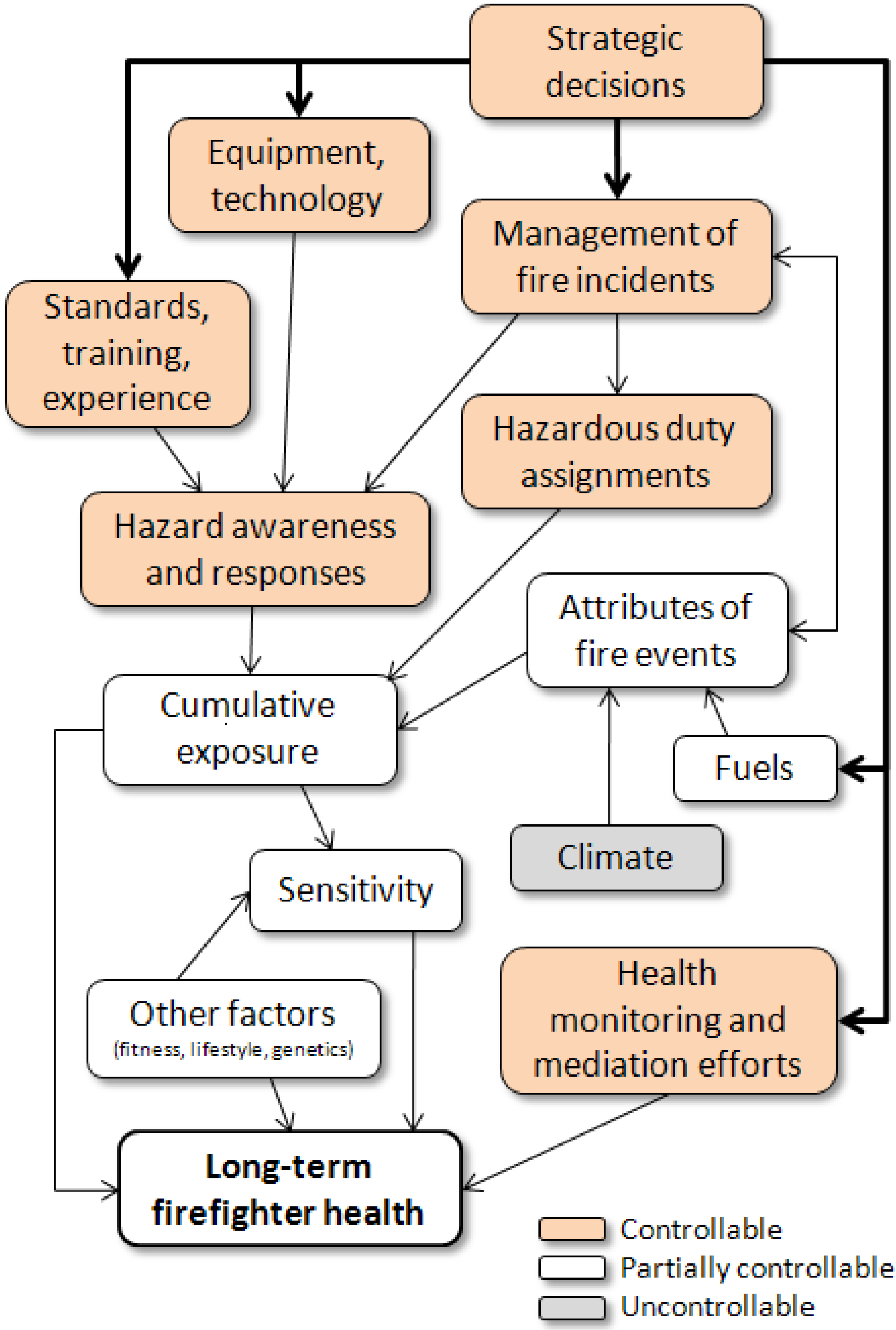


Figure 16. Conceptual model of smoke impacts.

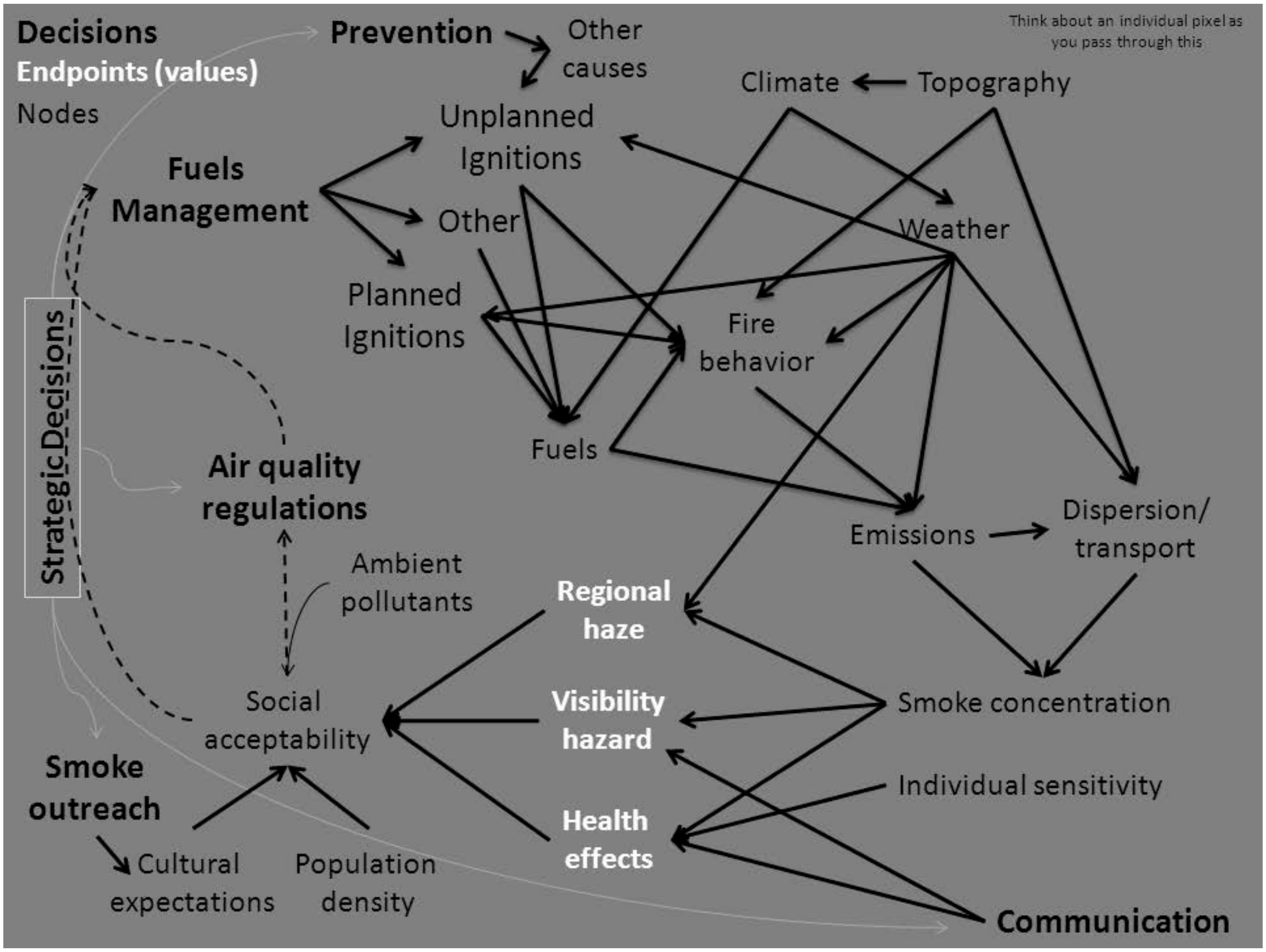
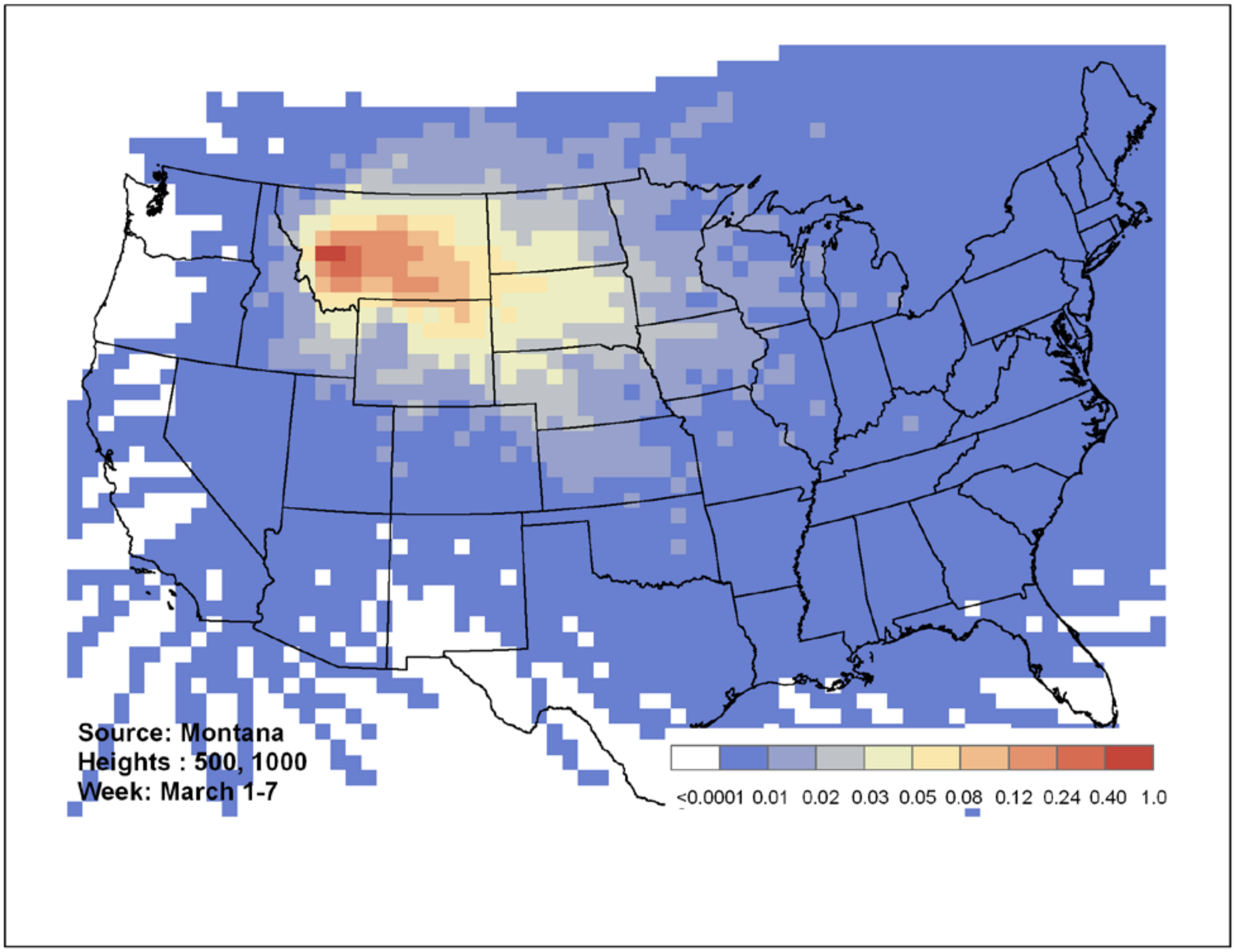


Figure 17. Potential smoke impact from a fire in Montana illustrating the need for a transfer function.



APPENDIX A

The following individuals contributed to one or more of the subteam efforts within the Phase II report.

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Calkin	Dave	USDA Forest Service
Carpenter	John	Department of Homeland Security
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Fay	Brett	Fish and Wildlife Service
Fitch	Mark	National Park Service
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Rollins	Matthew	US Geological Service
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Scranton	Samuel	Bureau of Indian Affairs
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Smith	Jim	The nature Conservancy
Smith	Rachel	USDA Forest Service
Spencer	Tom	Texas Forest Service
Stewart	Susan	USDA Forest Service
Strain	Jim	South Dakota Department of Agriculture
Sutphen	Ronda	Florida Forest Service
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Tripp	Bill	Karuk Tribe
Wein	Anne	US Geological Service
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