Pacific Northwest Research Station
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ASSESSING THE EFFECTS OF FIRE DISTURBANCE ON ECOSYSTEMS:

A SCIENTIFIC AGENDA FOR RESEARCH AND MANAGEMENT

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Abstract

A team of fire scientists and resource managers convened 17-19 April, 1996 in Seattle, Washington U.S. to assess the effects of fire disturbance on ecosystems. Objectives of this workshop were to develop scientific recommendations for future fire research and management activities. These recommendations—elicited with the Analytic Hierarchy Process—include a series of numerically-ranked scientific and managerial questions and responses that focus on: (1) linkages among fire effects, fuels, and climate, (2) fire as a large-scale disturbance, (3) fire-effects modeling structures, and (4) managerial concerns, applications, and decision support. At the present time, understanding fire effects and extrapolating fire-effects knowledge to large spatial scales is limited, because most data have been collected at small spatial scales for specific applications. Although we clearly need more large-scale fire-effects data, it will be more efficient to concentrate efforts on improving and linking existing models that simulate fire effects in a georeferenced format while integrating empirical data as they become available. A significant component of this effort should be improved communication between modelers and managers to develop modeling tools that can be used in a planning context. Another component of this modeling effort should improve our ability to predict the interactions of fire and potential climatic change at very large spatial scales. The priority issues and approaches described here provide a template for fire science and fire management programs in the next decade and beyond.

Summary

Fire and other large-scale disturbances have become an increasingly important issue as scientists, resource managers and society begin to embrace ecosystem-based management of natural resources. Although fire is recognized as an important component of ecosystem dynamics, the effects of infrequent, large-scale fire events have been difficult to quantify and model. The majority of fire-effects data has been collected at small spatial scales, while demands are increasing for large-scale applications in fire science and resource management. This leads to the potential for propagating substantial errors when extrapolating limited data to large spatial scales.

Future scientific efforts relevant to large-scale fire disturbance must encompass the concerns of both scientists and resource managers, and should be prioritized and sequenced in a logical way. This document describes the output of a workshop in which a team of fire scientists and public land managers developed an agenda for high-priority issues and activities relevant to fire disturbance. Individual working groups focused on: (1) linkages among fire effects, fuels, and climate, (2) fire as a large-scale disturbance, (3) fire-effects modeling structures, and (4) managerial concerns, applications, and decision support. It has been difficult for public agencies to accurately assess large-scale fire effects, and workshop participants agreed that future efforts in assessing fire effects should focus on fire phenomena at large spatial scales. Because it is unlikely that there will be sufficient financial and human resources to collect the information necessary to greatly improve our ability to quantify the effects of fire, it will be more effective to focus fire-science research and management activities on improving existing fire-effects models and linking them with other appropriate models.

This document contains a detailed articulation of critical issues—including specific scientific and managerial questions and responses—relevant to the large-scale effects of fire in North American ecosystems. The relative importance of these issues was ranked by workshop participants in a structured format using the Analytic Hierarchy Process, so priorities are quantified both cardinally and ordinally. These rankings provide the fire science community with a framework for guiding future research and management activities on fire effects and can be reassessed periodically as new information and models become available.

INTRODUCTION

From a human perspective, large and high-intensity wildland fires are one of the most dramatic phenomena in nature. Although they are infrequent temporally, they have large-scale impacts spatially: 1% of all wildland fires in the western United States may be responsible for as much as 98% of the land area burned (Strauss and others 1989). Large fires are responsible for rapid changes in vegetation, soils, biogeochemical cycling, microclimate, and many other ecological properties (Figure 1). Fire is the most important periodic natural disturbance in most forest, shrubland, and grassland ecosystems of western North America (Rogers 1996).

While fire is known to play a critical role in the long-term dynamics of most ecosystems, there are many difficulties associated with scientific assessment and management of large-scale fire phenomena. This problem was brought sharply into focus in 1988 during and following the large fires in the Yellowstone National Park region. Although paleoecological evidence indicates that fires of this magnitude (approximately 5,000 km^2 total land area) had previously occurred in the region (Romme and Despain 1989), agency resource managers, administrators, and the general public appeared to have limited awareness of the role of extreme fire events in Yellowstone ecosystems. Our ability to understand and manage for the effects of large fires has been limited by a lack of data at large spatial scales. There is a substantial scientific literature on the effects of fire in terrestrial ecosystems (e.g., Wright and Bailey 1982), but the vast majority of scientific data has been collected at scales of 10^{-1} to 10 km^2 (McKenzie and others 1996a). Applying these data to fire phenomena at much larger scales can result in substantial errors in estimating fire effects, because relevant processes are different at different spatial scales (Simard 1991, Table 1). The potential for substantial errors when extrapolating fire effects across spatial scales is particularly relevant for modeling fire and ecosystem processes.

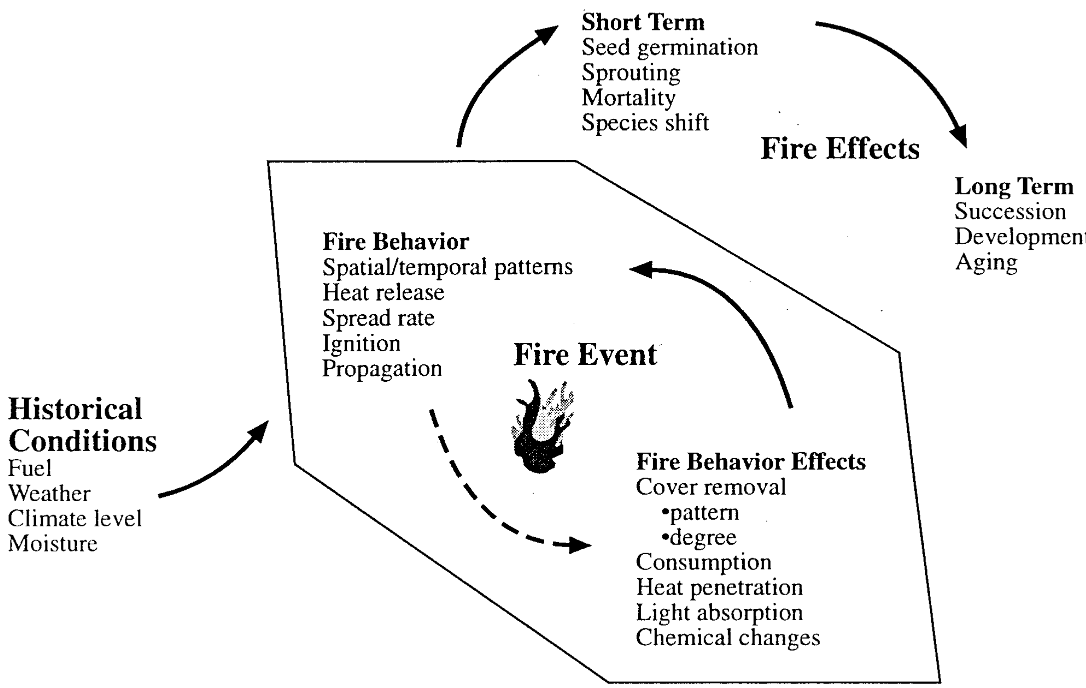

Figure 1—Large-scale fires have many effects and complex interactions. Figure drawn by David Weise and Timothy Paysen.

Simulation models have proven to be useful tools for predicting the effects of large-scale disturbance on ecosystems. Modeling is a convenient and practical alternative to the expensive and time-consuming collection of large amounts of data at large spatial scales. Models used to predict the effects of fire on vegetation can be grouped in three categories (McKenzie and others 1996a): (1) stand-level mechanistic and probabilistic fire behavior models, and first-order fire effects models, (2) stand-level successional models that incorporate fire stochastically, and (3) landscape-scale models of disturbance. These models operate on different spatial and temporal scales, although output from the first two types of models are often aggregated to larger scales.

Extrapolating ecological effects of fire across spatial scales can result in many sources of error, including: (1) extrapolating fire behavior models directly to larger spatial scales, (2) integrating fire behavior and fire-effects models with successional models at the stand level, then extrapolating upward, and (3) aggregating model inputs to the scale of interest. Regardless of which approach is used, extreme fire events pose a major problem for modelers due to the problem of propagating and compounding errors across spatial scales. The challenge is to develop or adapt models that are scientifically sound as well as applicable to resource management issues.

Spatial and temporal variation in fire disturbance in the Pacific Northwest varies widely by longitude, latitude, altitude and ecosystem type (Agee 1990, 1993), thereby providing a broad range of conditions for model development and testing. This region—generally considered to include Washington, Oregon, northern California, and southern British Columbia—contains a broad range of climatic conditions, geomorphic features, and elevations. This diversity of environmental characteristics is associated with many types of ecosystems including temperate rainforest, alpine meadows, east-side pine forest, and semiarid grassland.

The diversity of environmental conditions and ecosystems in the Pacific Northwest produces a variety of fire regimes, which can be defined by characteristics of the disturbance (Figure 2), characteristics of the vegetation, or fire severity (Figure 3) (Agee 1993). With respect to fire-severity classification, high-severity fire regimes have very infrequent fires (greater than 100 years between typically high-intensity fires) that often kill most trees in a forest stand (Agee 1990). Moderate-severity fire regimes have infrequent fires (25-100 years) that are often partial stand-replacement fires that include areas of high and low severity. Low-severity fire regimes have frequent fires (1-25 years) that are normally low-intensity fires with minimal impacts on forest overstories. Fires that occur in grassland and shrubland ecosystems tend to be in low- and moderate-fire severity regimes in terms of frequency but with rapidly moving, high-intensity fires.

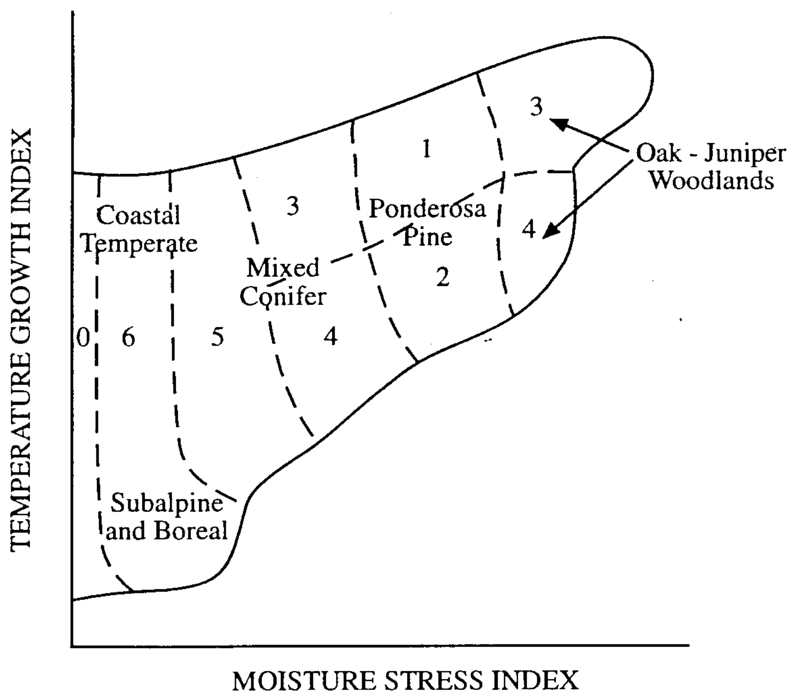

Figure 2—Fire regimes in Pacific Northwest vegetation types can be defined by physical characteristics of the disturbance (0=little fire influence, 1=infrequent light surface fire [>25 yr], 2= frequent light surface fire [1-25 yr], 3=infrequent severe surface fire [> 25 yr], 4= short return interval crown fire and severe surface fire [25-100 yr], 5=long return interval crown fire and severe surface fire [100-300 yr], 6=very long return interval crown fire and severe surface fire [>300 yr]). From Agee (1993), reproduced by permission, Island Press.

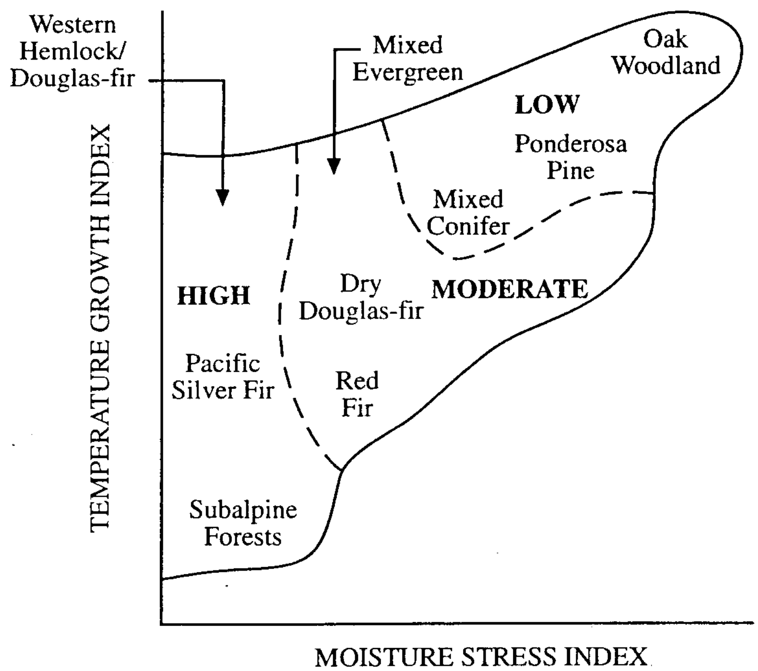

Figure 3—Fire regimes in the Pacific Northwest can be defined by fire severity. Stands in low severity fire regimes have <20 percent of basal area removed by fire, and stands in high severity fire regimes have >70 percent basal area removed. From Agee (1993), reproduced by permission, Island Press.

Recent large fires (over 800 km^2 land area in 1994) in forest ecosystems on the east side of the Cascade Mountains have posed a number of ecological, managerial, and political problems. It has been suggested that current forest management practices and fire exclusion (active through suppression, passive through alteration of fuel patterns by humans) may have facilitated these large fires, pushing the fire regime from low-severity to moderate- or high-severity. In addition, age-class and fire-scar data indicate that infrequent, very large fires on the west side of the Cascade and Olympic Mountains have burned greater than 10,000 km^2 in some years (Henderson and others 1989). The stochastic nature of these events and the large spatial scales at which they occur have proven difficult for scientists to analyze and for public agencies to manage. While it has been suggested that appropriate vegetation and fuels management can mitigate fire severity or restore fire regimes that existed during the past few centuries, the large spatial scales of extreme fires complicate postfire assessments and modeling efforts.

Given the complexity of large-fire phenomena, how do we improve our current scientific assessment and management of natural resources with respect to fire disturbance? How do we deal with a wide range of fire regimes in the ecologically diverse Pacific Northwest? We cannot afford to wait for decades for the data and techniques that would improve our understanding and managerial approaches to fire disturbance in ecosystems. We need to establish priorities now in order to optimize research programs, develop resource management strategies, and encourage cooperation between scientists and managers in the years ahead.

On 17-19 April, 1996, a group of scientists and resource managers gathered at the Fire-Disturbance Workshop on the University of Washington campus to discuss these issues. The objectives of the workshop were to: (1) identify the current state-of-knowledge with respect to fire effects at large spatial scales, (2) develop priorities for a scientific approach to modeling large-scale fire disturbance and its effects, and (3) develop priorities for assisting scientifically-based decision-making with respect to fire disturbance in resource management. While the focus was on the Pacific Northwest, issues of broader national and global concern were also addressed. A structured workshop process was used to conduct workshop discussions, compile information, and elicit knowledge from participants. Our previous experience with technical workshops (J. Peterson and others 1992, D. Peterson and others 1993, Schmoldt and Peterson 1991) demonstrated that *a priori* structure is important for achieving useful workshop results efficaciously.

In preparation for this workshop, there were a number of objectives, both strategic and tactical, that we sought to achieve during and after the meeting. Strategic objectives for this workshop are listed above and in the straw document (Figure 4. These objectives deal with the overall accomplishments proposed for the workshop, that is, describing, assessing, prioritizing, and recommending large-scale fire-disturbance research and managerial needs. A detailed tactical plan for achieving the strategic objectives was also developed; it is described briefly in Schmoldt and Peterson (1997). Tactical objectives for the organization and conduct of the workshop were threefold:

> *Content* — To elicit expert judgment regarding large-scale fire disturbances that could be used to guide future research and resource management efforts by the USDA Forest Service and cooperators, particularly in the Pacific Northwest Region.
>
> *Efficiency* — To collect these judgments within a short time frame of two days.
>
> *Product* — To collect this expertise in a detailed and structured manner so that results could be formulated into a publishable report (this publication) that reflects the current state-of-knowledge about large-scale fire disturbance and future scientific and managerial needs.

The *organization* and *process* of the workshop were designed with these tactical objectives of content, efficiency, and product in mind. The decision-making and group discussion protocols that were developed include three main parts: (1) assignment of attendees into discrete workgroups, which were the foci for workshop discussions, (2) a conceptual structure for organizing workgroup discussion, a context for the discussion content, and (3) a seven-step process for workgroup conduct that streamlined identifying, assessing, prioritizing, and recommending research and managerial needs. Workshop discussion centered around four broad content areas, or *primary topics*: (1) linkages among fire effects, fuels and climate, (2) fire as a large-scale disturbance, (3) fire-effects modeling structures, and (4) managerial concerns, applications, and decision support. Because these topics are relatively disjoint and workshop attendees possessed very specialized knowledge regarding these topics, we opted for small *workgroups* rather than one large plenary session. Each workgroup consisted of four to six members, dealt with a single fire topic, and had a discussion leader and a recorder. Members of each workgroup were given considerable freedom to move about and participate in other workgroups as appropriate.

Each workgroup was instructed to develop key questions for their assigned topic. Then, for each key question they were asked to provide corresponding responses. Workgroups were also asked to prioritize their list of key questions and, separately, their lists of responses within each question. Priorities were assigned for both importance and for feasibility (or doability or practicality). The Analytic Hierarchy Process (Saaty 1980, 1990) was used within this group setting to arrive at priorities. This conceptual structure is depicted graphically in Figure 5. Following the workshop, statistical analyses were performed to determine which key questions (and which responses within each key question) differed significantly in priority. Lists of key questions, responses, and their priorities for importance and feasibility could then be used to form recommendations regarding large-scale fire-disturbance modeling. Because this document records fire workshop results, and not methodology, we do not elaborate further details on the workshop's conceptual structure and process. Readers are referred to Schmoldt and Peterson (1997) for specific methodology.

Workgroups met for discussions all day on the second day of the workshop, and for about two hours on the morning of the third day to tie up loose ends and discuss final results. After a morning break on the third day, a member from each workgroup made a summary presentation to the plenary session. This allowed other attendees of the workshop to ask questions or to offer suggestions. It was felt that constructive, intergroup feedback of this sort would enable each group to further improve their analyses and final report.

Each of the following four sections describes issues that were addressed, and results produced, in workgroup discussions. Despite the overall conceptual structure provided for the workgroups, each topic is different in difficulty, current knowledge, and available information. These differences dictated adjustments to the discussion process to fit specific needs. Consequently, each workgroup's report varies in style, level of detail, and extent.

Figure 4—The strawman document was used to generate discussion by suggesting key questions and responses for the four workgroup topics. Workgroup participants had the option of using these questions and responses, modifying them, or developing their own.

LINKAGES AMONG FIRE EFFECTS, FUELS AND CLIMATE

What are the critical scientific issues regarding the impacts of fire on vegetation and fuels?

- “Natural” and human-related conditions interact to affect both vegetation and fuels. Natural factors tend to be stochastic. Human factors tend to be planned, although consequences are not necessarily predictable.
- The long-term impact of changes in fire frequency on vegetation is poorly quantified for most systems.
- Landscape-level changes (e.g., ecosystem distribution) resulting from fire frequency, size, and intensity are poorly understood.
- The short-term impact of changes in fire severity on vegetation is better known for many systems.

What are the critical management issues regarding the impacts of fire on vegetation and fuels?

- Acceptable levels of impacts on vegetation and fuels need to be stated: emissions, fire size, timber resource, watershed protection, exotic vegetation, etc.
- Management objectives for vegetation composition and fuel loadings need to be clearly stated.
- Long-term perspectives are needed for management of landscapes and ecosystems.

What are the critical political issues regarding the impacts of fire on vegetation and fuels?

- Air quality: emissions must be restricted.
- The role of prescribed burning as a management tool for modifying vegetation and fuel loading should be assessed.
- Social impacts (human safety and health, economic values) of prescribed burning and wildfire need to be assessed.
- Legal and logistic concerns with respect to political boundaries need to be reconciled. Cooperate among institutions as much as possible.

How can the relative impact of fuels and weather on fire regimes (frequency, intensity, size, etc.) be quantified?

- The relative variability of weather and fuels needs to be quantified in a “meaningful” way. The relationship of this variability to impacts on ecosystems must be examined.
- The relative impact of fuels and weather will vary for different ecosystems.
- Historical fire data and climatic data need to be examined more rigorously in different ecosystems. This can be done in conjunction with fire behavior modeling.
- Fire behavior modeling needs to be related to changes in landscape patterns of vegetation and ecosystems.

FIRE AS A LARGE-SCALE DISTURBANCE

What are the most important aspects of long-term changes in fire characteristics on vegetation?

- Spatial patterns of vegetation distribution and abundance are sensitive to changes in fire characteristics.
- Fire frequency, size, and intensity affect postfire vegetation composition.
- Fire frequency affects successional patterns with respect to vegetation composition and structure. The relative impact varies greatly among ecosystems.
- Fire size affects landscape patterns (e.g., patch size) and vegetation composition (through rate of vegetation establishment).
- Fire intensity affects postfire structure and regeneration.
- Fire occurrence in ecosystems that were previously fire-excluded can alter landscape patterns and disrupt previous ecosystem structure and functional relationships.

What is the current state-of-knowledge regarding the long-term interaction of fire, vegetation, and climate?

- Fire frequency is affected by large-scale climatic patterns.
- Climate affects distribution and abundance of species on the landscape; species composition of ecosystems is dynamic at large temporal scales.
- There is some evidence that large-scale changes in vegetation affect large-scale climatic patterns.
- Climate affects the distribution and composition of fuels, which in turn affect the size, frequency, and intensity of fires.

What aspects of fire as a landscape/ecosystem disturbance are relevant to large-scale (spatial and temporal) modeling? What aspects are particularly relevant in the Pacific Northwest?

- Fire induces changes in decomposition, biogeochemical cycling, and energy cycling
- Impacts of large fires occur at very large scales. Systems are not in true equilibrium, even over thousands of hectares and thousands of years.

- Spatial patterns of vegetation distribution and abundance are sensitive to changes in fire characteristics.
- Fuel conditions are relevant at small and large spatial scales and change temporally.
- Weather data and conditions are normally relevant at large spatial scales. Note: weather and topography often interact on small spatial scales. Because they impact fuels, and fuels are relevant at small scales, weather can be relevant at small scales also.
- Fire occurrence is stochastic, but has a causal component (not random). Events are often modeled as random (probabilistic) because we do not fully understand, or cannot project, the underlying mechanisms.
- Fire characteristics vary latitudinally, longitudinally, and altitudinally (east side vs. west side, northern vs. southern forest types, low elevation forest vs. subalpine).
- West side systems tend to have less frequent but larger fires than east side systems.
- Pioneer species (e.g., alder) can rapidly alter vegetation distribution following fire.

FIRE EFFECTS MODELING STRUCTURES

What existing models (or components thereof) could be adapted or modified for proposed work by USFS-PNW and the University of Washington? What modeling approaches can be used with minimal collection of new data?

- FARSITE
- FIRESUM
- FEES
- FIRE-BGC
- LOKI
- MAPSS
- TEM
- Fire-behavior models
- General circulation models
- Need to consider whether steady state or transient modeling approach is appropriate.
- Need to clearly address transitions in vegetation types and fuel loading.

What are the relevant scale issues (spatial and temporal) related to modeling fire impacts on vegetation and fuels?

- The appropriate scale of resolution needs to be determined for each modeling effort.
- Models need to be designed to minimize errors in extrapolation to larger scales.
- Variation in vegetation and fuels and their response to fire may be different at different scales.
- Most existing data on fire effects was collected and analyzed at smaller spatial and temporal scales.
- Modeling needs to occur at one scale finer than the level of resolution desired for projection or management decisionmaking.
- Effects over spatial distances can often be aggregated in obvious ways; effects occurring over temporal distances often have no simple additive property. Among other things, this means that these two types of scales (spatial and temporal) need to be addressed very differently.

What are some potential approaches for GIS-based modeling of fire impacts on vegetation?

- Design models to take advantage of GIS databases.
- Examine one or more GIS databases containing evidence of large and/or frequent fires. Search for patterns in different data layers.
- Link fire behavior models to GIS databases (containing fuels information) to generate landscape-level projections of vegetative changes resulting from fire.

How does one integrate climatic change scenarios in fire-vegetation modeling (for scientific or managerial purposes)?

- Need to determine whether steady state or transient modeling approach is more appropriate.
- A transient approach requires dynamic modeling of climate change, in particular, how fire-genic additions to atmospheric carbon and vegetative storage of carbon affect climate.
- A straightforward approach is to identify climatic conditions and rates of change for modeling purposes.
- It is important to understand and model the impact that climate change has on fuels.

MANAGERIAL CONCERNS, APPLICATIONS AND DECISION SUPPORT

How can a scientifically rigorous modeling approach be designed to be most useful to resource managers? How should scientist-manager communication be encouraged?

- Model logic should be sufficiently clear that managers can understand the modeling process and provide input to it.
- Manager input and participation in model-building will result in a better product.

- Regular exchange of information regarding modeling for a specific dataset (e.g., a GIS vegetation database) may facilitate dialogue between scientists and managers.
- Modeling should be adaptive, i.e. models should be continually revised as monitoring data suggest revisions. Monitoring and model revisions will require that managers and scientists work closely together.

What are the most useful model structures and outputs for resource managers, decisionmakers, and policy makers?

- Incorporating a probabilistic approach will provide a more realistic range of output rather than a single "answer." Note: while probabilities can be tracked, either rigorously or in an *ad hoc* fashion, generating multiple scenarios for particular inputs (as mentioned below) will be the most useful for managers. By using the most likely suite of input data, the most likely model output scenario can be generated. Likewise, less likely inputs will generate less likely future scenarios. As time passes, it will be apparent which suite of input data is valid and, therefore, which output scenario is likely to occur.
- Realistic and meaningful categories and classifications will be the most useful.
- Provide options for the model user that will allow for examination of realistic alternatives for areas of uncertainty (e.g., a range of climatic conditions rather than one assumed scenario).

How can decision support systems assist resource managers with fire effects issues in planning and operations?

- Decision support systems need to be straightforward and accessible to resource managers.
- Decision support systems need to be integrated with GIS and other landscape-level tools.
- Resource managers need the capability to generate multiple fire effects scenarios based on different climatic projections.
- Important thresholds in the modeling process and subsequent decisionmaking can be identified.
- Critical features of modeling can be highlighted without the need for resource managers to participate fully in the modeling process; they can then specialize in management and decisionmaking.
- Resource managers can use decision support systems in conjunction with expert opinion from scientists and other managers.

LINKAGES AMONG FIRE EFFECTS, FUELS, AND CLIMATE

JAMES AGEE, LARRY BRADSHAW, SHERI GUTSELL, EMILY HEYERDAHL (RECORDER), ROBERT KEANE (LEADER), KEN LERTZMAN, AND KEVIN MCKELVEY

Key Questions and Responses

This workgroup developed five questions important to understanding the linkages of fire, fuels and climate. These key questions are presented below in order of importance. For each question, the group generated some general statements about the question's subject matter to establish a context for response discussions. The group then produced a set of responses to each question that define current research and management needs. Each response was rated by the group on a final scale of 0-1 (using the methodology presented in Schmoldt and Peterson 1997) as to its (1) importance to management and research and (2) its "doability" as defined by the probability of successfully researching the problem described by the response and implementing a solution. In addition, each key question posed by the group received an Importance rating. Doability was not considered for the key questions because the workgroup felt that the breadth of the key questions made such a comparison extremely difficult. A summary of importance and doability ratings for the key questions and responses appears in Table 2.

There are certainly many more factors than fuels and climate that affect fire. The workgroup limited its discussion to just these factors because it believed they are the most important. Moreover, to include all processes that affect fire and its subsequent effects in this discussion would be intractable. Therefore, the first key question was composed to identify the causal mechanisms that are an important link to fire and fire effects. This question sets the stage for all remaining questions.

Question 1: What, where, and when are the factors important to fire disturbance?

The first important caveat is that *it is the interactions of these factors that are important to describing fire*; not simply the factors and processes taken alone. A comprehensive discussion of individual processes is helpful to understand the context of the fire environment, but it is how these processes interact that truly dictates fire dynamics. Because of dependencies between these factors the group decided not to generate importance or doability ratings for the responses to this first question. Instead, these factors are used as background for all other questions.

The first part of the question "What are the important factors?" was discussed in detail and we decided the following list would generally describe those factor processes important to fire, especially at the broad (or coarse) scales:

Climate — Controls extreme events, particularly where there are significant fuel loadings, and is a broad-scale process. Synoptic-scale weather patterns affect mid-to-fine scales, including surface temperature, precipitation, and fuel moistures (Balling and others 1992, Bessie and Johnson 1995, Brenner 1991, Clark 1990a,b, Johnson and Wowchuk 1993, Johnson 1992, Vasquez and Moreno 1993, Wein and MacLean 1983).

Fire — Behavior and effects. Wildland fire is the process that shapes landscapes and dictates species compositions (Albini 1976, Anderson 1969, Byram 1959, Crutzen and Goldammer 1993, Heinselman 1981, Johnson 1979, Johnson and Van Wagner 1985, Johnson 1992, Johnson and Larsen 1991, Masters 1990).

Fuels — Dead and live organic matter that contributes to the combustion process. Fuels include both living and dead vegetation, and is highly influenced by vegetation structure. It is fuels that control fire when weather is not extreme (Brown and Bevins 1986, Brown and See 1981, Frandsen and Andrews 1979, Spies and others 1988, van Wagtendonk 1972, Williams and Rothermel 1992).

Biota — All living things in the fire environment. The type of vegetation affects live and dead fuel characteristics and the nature of fire behavior. Fire effects vary widely depending on resistance of organisms to fire and growth and regeneration after fire (Agee 1993, Bond and van Wilgen 1996, Goldammer and Jenkins 1990, Johnson 1979, Johnson 1992, Prentice and others 1993, Wright and Bailey 1982).

Physiography — Defined by slope, aspect, landform, slope shape, slope position, and elevation. Topography directly influences the orientation of the fuel bed and indirectly controls landscape composition and structure (Albini 1976, Andrews 1986, Fensham 1990, Rothermel 1972, Swanson and others 1990).

Humans — Land-use and land management often influences fire and ecosystem dynamics on the landscape (Pyne 1982, 1984).

The workgroup developed several general statements that address spatial and temporal aspects of fire processes.

- Extreme fire events currently burn the most area. It is estimated only 1 percent of the fires burn over 98 percent of the land area (Johnson and Wowchuk 1993, Strauss and others 1989).
- Extreme fire events are controlled by climate (Bessie and Johnson 1995, Johnson 1992, Johnson and Wowchuk 1993). Extended drought is the primary factor responsible for severe fire seasons. Extreme fire events burning during these droughts are usually wind-driven and are of such high intensity that the other factors listed above have an insignificant effect on fire behavior.
- Fuels, topography, weather, humans and the biota are the major factors that influence fire dynamics in non-extreme years.
- Fire behavior in the non-extreme years affects heterogeneity in landscape composition, pattern and structure (Arno and others 1993, Forman 1995, Forman and Godron 1986, Marsden 1983, Pickett and White 1985, Turner 1989, Turner and Gardner 1991, Turner and Romme 1994).

After these statements were made, it was evident that research could provide important information needed by resource managers. The following is a small set of need statements generated by the workgroup.

- Need to identify and predict the conditions of those factors that enable extreme (severe) fire events.
- Need to understand and integrate the role of all factors and processes to fire dynamics.
- Need to compute the probability of large-scale disturbance events and to evaluate risk.

After careful deliberation, the workgroup decided that there was a set of questions that would not be discussed because of the short discussion time. These are important questions that research must investigate but the workgroup could not address in detail.

- What other human-oriented factors influence these linkages? More specifically, how do society, politics, and culture influence processes and interactions in the fire environment?
- What was the role of native peoples and their interactions with fire process linkages? Did native peoples change the pattern of fire or complement existing patterns?

Question 2: What do we know about these linkages?

The workgroup assessed existing knowledge about processes affecting coarse-scale fire dynamics to identify possible research areas. This knowledge base could be in the form of literature, models, databases, spatial data layers, and expert systems. Responses were stratified by individual fire-related processes, recognizing interactions are important. Some broad statements were developed to provide a context for our inventory of fire-process knowledge.

Climate

Large-scale synoptic events have a quantifiable historic frequency and fire effect for recent periods (post-1940) (Arno and others 1995, Barrett and others 1991, Heinselman 1973, Johnson 1979, Johnson and others 1990, Johnson and Larson 1991, Masters 1990, Reed 1994). These climatic events include mid-tropical anomalies (Johnson 1992, Johnson and Wowchuk 1993) and El Niño Southern Oscillation (ENSO) events (Brenner 1991, Swetnam and Betancourt 1990). There is subcontinental variability in the timing and magnitude of major climatic events (Clark 1990a, Clark and others 1996, Johnson 1992). The extremes of these events, either very wet or very dry periods, dominate the fire environment. Between the extremes, the short-term weather, fuels and topography have a stronger influence on the fire environment. At some point, the fire-environment dependency switches from fuels/weather/topography to climate (after a long period of hot, dry weather) and "enables" landscapes to burn regardless of composition, structure, and pattern; however, this threshold of change is unknown. We also know that when an ecosystem is in an "enabled" state, large-scale disturbance may not occur due to other factors such as lack of ignitions and wind. Large-fire years are important because large fires burn most of the total area burned, and these fires are typically the most severe and intense.

Current Knowledge of Climate and Climatic Data

<u>Long-term climatic records</u>

General trends can be inferred from paleoclimatic records, such as packrat middens, pollen records, charcoal, ice cores (<10,000 years), tree cores (<4,000 years), sunspot records (Allison and others 1986, Arens 1990, Gajewski 1987, Hopkins and others 1993, Singh and others 1981, Swain 1973, Swetnam and Baisan 1994). These data sources may be loosely correlated to large-scale disturbance patterns.

Current climatic records

These data are reliable but limited in spatial and temporal scale (circa 1900 to present). Most data have maximum and minimum temperatures and precipitation. Data quality and length of record are highly variable. Sources include U.S. National Weather Service Climatic Data Centers and Canadian Atmospheric Environment Service (50 to 100 years B.P.), U.S. Natural Resources Conservation Service (SNOTEL) (1980 to present), USDA Forest Service and Bureau of Land Management (BLM) fire weather networks.

Simulation models such as MTCLIM (Hungerford and others 1989), PRISM (Daly and others 1994), and DAYMET (Thornton and others, in press) are useful for extrapolating weather data from base stations across mountainous terrain. Continuous spatial data layers can be constructed for any number of time intervals and areas.

Climate models

These include general circulation models such as UKMO and GISS, with mechanistic regional-scale models such as RegCM. These models will be increasingly useful, but there are no known long-term stochastic or empirical models for spot-weather forecasts (Fosberg and others 1993, Shands and Hoffman 1987). Global-scale models probably do not contain sufficient detail to accurately capture or define the establishment of "enabled" states of risk, although research efforts are underway to develop finer spatial-scale resolution weather predictions from GCM output.

Fuels

Of the six fire factors listed in Question 1 above, we know the least about fuel dynamics. It is generally accepted that fuels are highly variable in time and space. Fuels are very important in small- and moderate-scale fires but less important for extreme fires (Bessie and Johnson 1995). Fuel loadings are more dependent on vegetation than weather in the short term but, in the long term, it is climate that ultimately dictates the rates and magnitudes of fuel dynamics (for example, fuel moisture, decomposition). Most fuel studies substitute space for time in the sampling scheme rather than use permanent plot remeasurements. This results in both across- and within-site errors. Probably the most important fuel characteristics that affect fire dynamics are bulk density, loading, surface area-to-volume ratio, vertical and horizontal continuity, moisture content, and live-versus-dead fraction (Brown 1981, Brown and Bevins 1986). However, the most important fuel variables that affect ecosystem dynamics are probably loading, coarse woody debris (size, length, rot), duff depth and distribution, snag density, moisture content, and particle distribution.

Linkages between fire and fuels are different than linkages of fuels to other ecological processes. Many ecological processes and ecosystem characteristics are strongly influenced by very large fuels. Moisture retention in these large particles is largely controlled by saturation during rainy periods or in the winter. Fire, on the other hand, is strongly affected by quantities of fine fuels and their moisture contents which vary day-to-day with atmospheric humidity. Under low to moderate fire weather conditions, large, ecologically important elements will often be only partially consumed by fire. However, in extreme drought conditions, these large logs burn over long time periods under smoldering and direct combustion processes. Long fire-residence times, even if fire intensity is not extreme, can cause root and cambium mortality and contribute to plant mortality (Peterson and Ryan 1986, Ryan and Reinhardt 1988) and changes in properties (Albini and others 1996, Wells and others 1979).

Available Temporal Fuels Data

There are very few studies of temporal variation of fuels in the United States using permanent plots. Some studies include the Sierra Nevada, Yosemite National Park (seven years and ongoing), Yellowstone National Park (Renkin and Despain 1992), western Cascades (Spies and others 1988), western Montana, (five years and ongoing, Keane and others 1996b), Coconino National Forest (Arizona, 20 years and ongoing), Francis Marion National Forest (South Carolina, 30 years and ongoing), and Appalachicola National Forest (Florida, 30 years and ongoing).

Available Spatial Fuels Data

Most fuels inventories have substituted space for time in their sampling approach, and these studies usually are stand-based approaches. Examples are presented below.

Fuel descriptions - photo series (Fischer 1981)

Fuel data bases - (Brown and See 1981, Jeske and Bevins 1976)

Sierra Nevada Ecosystem Project (SNEP 1996)

Montana/Idaho - gradient remote sensing study (Keane and others 1996b)

Fuels maps or geographic information system (GIS) layers (Hardy and others, in press)

EROS fuel map - (Loveland and others 1991, Hardy and others, in press)

Future fuels (Photo series under development by Forest Service research stations)

Simulation models -- Many mechanistic vegetation models can be used to simulate fuel dynamics, for example Keane and others (1989), Keane and others (1996c); also see Shugart and West (1980).

Fire

Fire is, or was, the primary disturbance process in most North American ecosystems. There is an important difference between fire intensity and fire severity. Fire severity is related to fire effects and describes the influence of a fire on the biota, whereas fire intensity is related to fire behavior and describes the physical characteristics of the fire. We must know fire severity, intensity, seasonality, and pattern to understand the linkages and interactions in fire dynamics. The most important fire behavior characteristics are listed in below. The variability of fire intervals may have a major effect on the character of the vegetation.

- Fuel consumption (kg m-2)
- Rate of spread/intensity (m sec-1, kW m-1)
- Duration (smoldering vs. direct combustion)
- Size and pattern (ha)
- Soil heat pulse (oC)
- Frequency (yr-1) and its variability
- Surface versus crown fire
- Smoke and emissions (kg ha-1)
- Propagation processes
- Spot-fire mechanisms
- Ignition dynamics (sources, fuel bed, moisture)

Fire Models

There are several spatial and nonspatial fire models available. Among them are BEHAVE (Andrews 1986), FARSITE (Finney 1994, Finney 1995, Finney and Ryan 1995), Canadian Fire Behavior Prediction System (van Wagner 1987), and cell automata models (Clark and others 1994). However, all of them have some limitations including: developed to model surface fires, crown fire simulations are limited, no specific link to fire effects, scale dependent, require specific fuels and forest structure, difficult to field test and validate, developed for homogenous fuel conditions, assume all areas within a “cell” defined by the model, burn without islands of unburned vegetation, and limited incorporation of spot fires.

Fire-Effects Models

There are a limited number of fire-effects models. They include CONSUME (Ottmar and others 1993), FOFEM (Keane and others 1994, Reinhardt and others 1996), empirical equations (Brown and others 1985), mechanistic models (Peterson and Ryan 1986), BURNOUT (Albini and others 1995, Albini and Reinhardt 1995), smoke dispersion models (PUFF, CALPUFF, EPM, Harrison 1996), and soil heat-pulse models (Albini and others 1996). These models have some of the same limitations of the fire-behavior models including: limited scope (geographical, ecological, vegetation), focus is on vegetation and fuels but no other processes, high variability in reliability, scale dependent, difficult to field test and validate, developed for homogeneous forest conditions, and assume fires burn entire stand.

Emission-Production and Smoke-Dispersion Models

Emission-production and smoke-dispersion models do not have the same limitations as other fire-effects models. Emission-production models (e.g., EPM, Sandberg and Peterson 1984) and smoke-dispersion models (e.g., NFSpuff, CALPUFF, SASEM, TSARS+, and VSMOKE, Breyfogle and Ferguson 1996), consider topography and atmospheric conditions and require results fro fuel consumption models as inputs. They are too difficult to test and validate, but are designed for a broad scope of applications and varying spatial and temporal scales.

Historical Fire Records

There have been over 300 fire-history studies in the United States and Canada since the 1940s). Most of these studies have been in the western United States and Canada. These fire-history studies have characterized fire frequency quite well, but few have investigated the spatial extent of fires. Most studies have been in dry, low-elevation vegetation types that have the most fire scars and where fire is relatively frequent. Subalpine and alpine environments have not been studied as often, and fire-history records are often incomplete. There are also some methodological problems with study designs that may reduce the spatial scale of inferences.

Fire-history studies have been very successful in the last 50 years in quantifying the frequency, severity, and extent of wildland fires in forested ecosystems (Arno and others 1993, Baker 1989, Barrett and others 1991, Foster 1983, Johnson 1979, Johnson and Larsen 1991, Johnson and others 1990, Masters 1990, Swetnam and Baisan 1996). There seem to be three primary methods to measure recent fire histories. Charcoal sediments in varved lakes provides a general description of fire frequency. Dating fire scars on tree and shrub stems probably provides the most accurate method of quantifying fire frequency (Johnson and Gutsell 1994). However, these are point records and do not always accurately describe the extent and severity of fire. Tree and shrub age distributions can be used to date the last fire in a stand, and, if all stands are dated, then the extent and possible severity of fire can be assessed (Johnson and Gutsell 1994, Yarie 1981).

It is critical to preserve, sample and analyze the fire-disturbance records on the landscape. This means that a sincere effort must be made to identify, locate, measure, and analyze landscapes that contain disturbance records such as fire scars and forest stand development data. Research such as fire scars, in particular on stumps, will disappear after wild fires and prescribed fires.

Archival documents.

There are many sources of historical fire records that may be used to characterize and study wildland fire. The U.S. General Land Office has archival documents of land-survey data that may be useful to describe vegetation composition and structure (Habeck 1994). The Forest Service and BLM have fire reports complete for most fires since about 1970. Many Forest Service and BLM districts have hand-drawn fire atlases that coarsely define fire boundaries. However, these records have some serious limitations. First, they are not consistently reported across agencies and geographical areas. Second, most are not accurately defined spatially or are temporally inaccurate. Third, many of these documents are difficult to obtain, read, and enter into a standardized data base or georeferenced data base.

Photograph chronosequences.

Past photo sequences provide a qualitative description of fire severity and extent (Gruell 1983, 1985). Photo series can be aerial photos, ground-based (orthophotos), or satellite images. The major limitations of these photos are that fire-regime characteristics cannot be measured. Landscape pattern can be delineated, but fire frequency cannot be described quantitatively without ground sampling. High-severity fire regimes are better analyzed this way than low-severity regimes with more uniform forest canopies.

Historical forest maps.

These maps and GIS layers contain some representation of age and size class structure such that the year of the disturbance event that created the stand can be estimated. Unfortunately, many of these maps are inconsistent, inaccurate, and often inappropriate for fire history dating. They probably are appropriate only for crown-fire regimes, because their ages are often based on heights, and the maps often assume fire is the only disturbance. In addition, small polygons are often missed.

Timber and range inventories.

Each agency performs an inventory of its own lands. However, these inventories are not comprehensive for fire applications, because they are geared toward resource quantification rather than fire size and date. Additionally, they contain mostly descriptive information on fire. Forest Inventory Analysis plots established by the Forest Service and other agencies may be an important source of temporal tree dynamics.

Anecdotal accounts.

While unquantified observations may be the only available information in some cases, these sources are subjective and often inaccurate.

Bog and lake cores.

Fire frequency estimates from cores taken from sediments are coarse-scale descriptions of fire frequencies (Clark 1988a,b; Clark and others 1996). They are useful only for identifying certain time periods when large fires burned in close proximity to the lake (Clark and others 1989). Interpretation of these cores is limited in time and space because cores can include a period that may be as many as 4,000 to 8,000 years B.P. These estimates are from point sources and it is difficult to make any generalizations about the spatial frequency and extent of fire in surrounding areas.

Current fire records.

Many government agencies are required to record some coarse descriptions of fires and their effects, and although some of these records are now in standard formats, there is relatively little information on fire effects at large spatial scales. Fire atlases are available at many Forest Service and BLM district offices.

Biota

This includes all living things that comprise an ecosystem. It was recognized that genetic variability of the biota will be important as climates and fire regimes change. Species and plant responses to climate and fire regime change are individualistic and occur mostly during the establishment stage. Rates of species change will be more directly related to changes in fire regime than direct species-climate interactions. Indeed, fire creates conditions that accelerate the change in species composition as it relates to climatic change. Patterns on the landscape will dictate adaptations, distribution, and migration of species. Landscape changes will be rapid at first, then will slow as fire, biota, and climatic conditions equilibrate. However, landscape-biota response to fire and climatic change will be less dramatic than stand-level responses. Future climatic and fire regimes will create some unique plant assemblages, perhaps even create communities that never occurred historically. Generalist species may tend to predominate on future landscapes at first (Flannigan and van Wagner 1991, Shands and Hoffman 1987).

Simulation Models

There are many models that simulate successional dynamics. These models are empirical, stochastic, process-based, or mechanistic (Shugart and West 1980). Most vegetation dynamics models are stand-based, but several landscape-level, spatially-explicit models have been developed. Probably the most commonly used vegetation models are the gap-phase models first pioneered by Botkin (1993) with the JABOWA model. Among the models that include fire dynamics are FIRE-BGC (Keane and others 1989), SILVA (Keane and others 1996c), FIRESUM (Kercher and Axelrod 1984). Other models include SIMFOR (habitat supply model), DISPATCH (Baker 1993), CRBSUM, LANDSUM, (Keane and others 1996a), VDDT, and FVS (formerly PROGNOSIS, Wykoff and others 1982).

Conceptual Models

There are many conceptual and diagrammatic models that simplify the succession process. Most notable is the multiple-pathway approach of Noble and Slatyer (1987) and Cattelino and others (1979). Kessell and Fischer (1981) integrated these concepts into a management-oriented model. Kessell's (1979) gradient model also describes and quantifies the successional gradient and correlates this gradient with environmental conditions. Fischer and Bradley (1987) used these concepts for a simplified mid-scale succession model. Arno and others (1985) and Steele and Geier-Hayes (1989) integrated the successional "pyramid" concept developed by Hironaka (1989) into a management-oriented classification of successional community types in a habitat type. See Bond and van Wilgen (1996) for more conceptual fire-succession models.

Expert Systems and Artificial Intelligence

There has been a recent explosion of vegetation models based on expert systems and artificial intelligence (AI), in which parts of the above models are incorporated in their architecture. Chew's (in press) model SIMPLLE is a good example of a successful AI application of succession modeling. Also, the Fire Effects Information System (Fischer and others 1996) includes successional information with an inference engine.

Databases

Most land management agencies, and the Forest Service in particular, have extensive databases describing successional processes. Most databases have substituted space for time in their sampling strategies so there are high geographic and site variabilities inherent in the data. However, there are some temporal data sets that go back 30-50 years. Stickney (1985) has a comprehensive temporal successional data set from western Montana.

Spatial Data

There are many sources of spatial data that can be used to quantify succession. Fine-scale sources include historical and current land management plan maps (habitat types, potential natural vegetation), aerial photos, and archived records. Coarse-scale sources include Küchler potential vegetation maps, Bailey's ecoregions map, Society of American Foresters maps, satellite imagery, Mission to Planet Earth satellite imagery products, and a host of other satellite and air-borne platforms. The limitation of most of these data is that they rarely go back more than 80 years, and in most cases, the historical record goes back less than 20 years.

Successional Classifications

There are many studies that have attempted to classify successional development after fire. See the annotated bibliography by Elliot and others (1993).

Autecological and Synecological Plant Information

There are abundant data in the literature on the response of plants to fire. Most are stored in the Fire Effects Information System (Fischer and others 1996).

Physiography

Physiography can be important in influencing fire dynamics, especially for smaller fire events, but few quantitative data or tools are available for assessing this important factor. Some studies have examined the effects of physiography on fire frequency and found them insignificant (Johnson and Larsen 1991, Johnson 1992, Johnson and others 1990, Masters 1990). Perhaps a more logical approach would be to identify those physiographic entities that can be controlled or managed, and include them in an assessment of landscape thresholds. Naturally, physiographic effects are probably applicable only to problems at small (up to a few hectares) to moderate scales (up to a few km^2), and their descriptions should only be pertinent to the issues at these scales.

Question 3: At what scales are processes important?

In questions 1 and 2, we attempted to provide a context in which to interpret the relative importance of research and management needs in the understanding and management of fire and ecosystems. These next three questions attempt to describe a working structure in which these research and management needs can be solved. The workgroup generated a set of responses (in italics) to these questions that try to capture the important factors that should be included in any research or management project.

Error propagation must be accounted for across scales. Accuracy assessment of predictive models, spatial data layers, and collected field data are essential for land management credibility. Innovative methods are needed to determine prediction errors so that land managers can provide the public with important information for interpreting land management treatments. Error characterization will hold researchers and management accountable for the tools and information used in management analysis.

An ecological data structure that spans many scales is needed. Data sampling, storage, and analysis structures that are hierarchically nested across temporal and spatial scales are badly needed by most management agencies. These structures must be scientifically based but directly applicable to management. Sampling methodologies must be developed to validate products derived from remote sensing and relational data bases. We need a ground-based sampling system that attempts to validate or test simulation models so the degree of error can be estimated. This task would be relatively difficult to accomplish.

A scale of analysis (e.g., landscape scale) must be defined to integrate coarse- and fine-scale processes. The scale of analysis for research and management activity investigations must be clearly defined. This scale of analysis can be spatially defined by a resolution level (such as 1:250,000 map scale) and a minimum mapping unit (such as 30-meter pixels or 10-acre minimum mapping unit). At the very least, the size of the analysis area needs to be triple the size of the largest disturbance to properly portray landscape dynamics and patchiness in a meaningful way.

Multiple scales should be incorporated in simulation approaches. Important processes must be assessed at appropriate scales. In addition, some "unimportant" processes (e.g., species migration, local weather, genetic plasticity) can become important as landscapes, fire and climates change, so they should be incorporated in any analysis. We will continue to need imagery and data products that span many spatial and temporal scales.

Explanatory coarse-scale models are needed to refine the predictive ability of other models. Process-based (mechanistic) and empirical models must be used in tandem for most management projects. Process-based models can be used to refine, modify, and identify new sampling areas for empirical models. Mechanistic relationships that are difficult to quantify using conventional means can be evaluated using empirical techniques. Coupling empirical and mechanistic (and even stochastic) models may allow a synergistic ecological application that is efficient, cost-effective, and timely.

*A cross-scale decision support tool is needed for managing wildland and prescribed fire***.** Decision support tools should include more than one scale of analysis (both time and space), and these tools should be compatible with each other. These decision support tools should present fire managers with a synthesized summary of all available scientific products and tools so that resources and people can be managed.

Fire characteristics must be intimately linked to weather and climatic processes. A system is needed that relates fire-season weather trends to fire extent, intensity, and severity. Given that the most land area is burned during severe fire seasons, tools must be developed to predict when these fire years can happen and to what extent they can be managed. Weather and climatic scales must be included in this tool. This task would be relatively easy to accomplish.

Question 4: How are linkages related in a landscape context?

Landscapes need to be engineered to lie within acceptable limits of fire behavior and severity and still function as an ecosystem. Tolerance limits or thresholds of natural and management activities need to be established for individual landscapes, and management activities should never violate established limits. In addition, large-scale experimentation should be conducted to identify these thresholds so biological diversity is conserved. How do we preserve refugia (e.g., areas where fire should be excluded to protect owls and grizzly bears) and still remain within acceptable thresholds? How many possible engineering solutions can one landscape have, and can a set of alternatives be engineered?

A method is needed for evaluating the effectiveness of vegetation- and fuel-management strategies at the landscape level. How is the relative success or failure of a land management strategy assessed across many temporal and spatial scales? Can a management action fail in the year after treatment but succeed after 10 to 100 years? Can a land management action that causes unacceptable disturbance consequences in one stand result in an overall improvement of conditions across the landscape? A method or tool also is needed that can prioritize areas in the greatest need of vegetation and fuels management. This task would be relatively difficult.

A better understanding is needed of the influence of linked processes to landscape structure, composition, and function and vice versa. How do coarse-scale properties of fire, climate, and physiography affect the dynamics of landscape-ecosystems? What is the "resilience, plasticity, and hardness" of a landscape to withstand, absorb, and incur disturbance, whether man-caused or natural? We need to define the "role" of exotic plants, animals and fungi in ecosystems so their impact can be managed (Christensen 1990).

Need to predict fire regime from the other ecosystem processes. Can, and should, fire be reintroduced to some ecosystems without adversely affecting other ecological processes? A method is needed to evaluate this approach for landscape planning. The most appropriate fire regime must be introduced to ecosystems, and these regimes must take into account changes in climate, vegetation, human development, and exotic invasions.

Landscape representations and analysis procedures are needed that are useful to both research and management. Statistical tools and indices are needed to assess, compare, contrast, and evaluate various management alternatives at a landscape level (Turner and Gardner 1991). Landscape metrics are needed that are useful for describing disturbance and vegetation properties. These indices and programs should be robust to spatial and temporal scale, and incorporate management attributes into their design.

A better understanding is needed of how the adjacency of vegetation patches affects and is affected by heat from fires. When do landscape patches act as fire breaks and when to they act as fire "enhancers"? How do patch characteristics affect coarse-scale properties as well as those ecosystem attributes that act across scales (e.g., wildlife, species migration, and insect populations). This task would be relatively easy to accomplish but would require an accurate accounting of contagion processes. Perhaps it can be done through an intensive analysis of fire-frequency studies.

A better understanding is needed of the dynamics of "fire breaks" spatially and temporally. More information is needed on the roles of natural and anthropogenic fire and fuels patterns and on the spatiotemporal conditions under which vegetation would act as a fuel break or a carrier of fire. Data are also needed on how fuel landscapes can be "subdivided" to limit or carry fire.

Question 5: What linkages are important to management?

The public needs to be encouraged to be actively involved in decisionmaking for ecosystem management. The success of ecosystem management (EM) will greatly depend on the ability of the public to understand and accept this land management philosophy. Everyone needs to understand the role of fire and its effects in each EM plan. Terminology should be understandable to both the public and professionals. Landscape changes and dynamics can be described such that the public will relate to them (e.g., fishing, aesthetics, remoteness, jobs). The integration of sound science with management practices should be explained in detail to the various publics.

Scientists must provide a summary of the state-of-knowledge to management. Scientists can no longer provide only information, tools and concepts for EM; they must also provide the training, utility, and context for this knowledge. Researchers must make research readily available to management in a timely fashion. But research should also synthesize these results in a useful manner and provide for their interpretation in a management context. In addition, researchers should strive to summarize research results for the public as well as the resource professional.

A physical measure of severity (with units) is needed that integrates frequency, variability, intensity duration, season, and synergistic effects of fire. This integration would be difficult to implement. Perhaps an index or number need not incorporate all the facets of fire regime, but it must be solidly based in physical science and describe process interactions rather than state variables. This index would provide a sense of validity to fire-effects measurements and predictions.

A system is needed to predict which processes enable fire events (risk) as they interact in both time and space. This is one of the most important issues facing resource managers. Better approaches are needed for predicting where, when, and how large-scale fire events occur. Specifically, a better method is needed for predicting the physics, dynamics, and effects of crown fires (Rothermel 1991) for all ecosystems across large land areas (such as a national scope).

Fire regimes must be described quantitatively in terms of severity and intensity. Fire potential should be characterized in terms of a landscape, not just a stand. This potential must be described in terms of the effect it will have on the biota. This description should be physically based and reference the index above. It is critical that EM projects have some quantification of fire severity to give them credence and validity.

Better predictions are needed of biotic responses for a wide range of fire and climatic conditions. Research must articulate, model, study and speculate, in simple terms, how and why fire, fuels, climate, and the biota will change as land management strategies are intensified and the climate gets warmer. This means a better ecophysiological characterization will be needed for plants and animals in the Pacific Northwest. A conceptual model must be developed that can be used to approximate the response of all biota to climate, fire, and fuels changes. Management treatments must be developed that do not cause adverse impacts under new climatic and management conditions.

A corollary to improved predictions is making them available to management and the public. Perhaps an important issue is how fire affects post-fire populations of insects, fungi, mammals, and people, and how fire and these factors act together to increase tree mortality. These tools should probably be mechanistically based so they can be expanded as climate, fire and biota change. Genetic variability must be incorporated into model and tool parameters to account for genotypic shifts in species abundance.

Technology is needed to manage large-scale events. All existing technology must be integrated in a synergistic application that will allow us to manage severe and large-scale fire events better and more efficiently. We can no longer afford to spend large quantities of money suppressing fires.

A system is needed to predict emissions from fire. In order to justify burning in ecosystems, a comprehensive system must be developed that predicts smoke production, dispersion, and health effects across many time and space scales. This system must have a mechanistic approach and account for the combustion of fuels, liberation of combustion products to the atmosphere, and dispersal of smoke.

A better understanding is needed of the interaction of these processes on smoke production. Smoke management will be one of the most important fire management issues in the twenty-first century. How should smoke effects be integrated and evaluated in a simulation approach? How should the effects of smoke on humans and ecosystems be communicated to the public.

Summary

The final listings of key questions, their responses, and rankings for each appear in Table 2. As noted above, the workgroup did not feel that they could make priority comparisons among the factors that impact fire disturbances because of the interrelated nature of those associations. Doability of the key questions was also difficult to determine owing to tremendous uncertainties. In addition to the tabular information in Table 2, the workgroup offered several general assessments of these linkages. First, besides the importance of the fire-disturbance factors listed, it is their interactions that are truly significant. This realization is also reflected in the importance rankings given to key questions 1 and 2. Second, extreme fire events are driven by climate, and through better understanding and predictability of their precipitating conditions researchers can greatly assist managers. Third, the probability of large-scale disturbances, combined with cost (= risk), needs to be computed more reliably. With respect to future needs, the workgroup noted that as fire suppression activities are reduced, due in part to cost and to an ecosytem-management view of fire as an important natural disturbance, smoke management will become a central fire-management issue.

FIRE AS A LARGE-SCALE DISTURBANCE

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Background

Simulating broad-scale disturbance is the *terra incognita* of fire modeling (Simard 1991). The process-based fire-behavior models cited in the previous chapter can be used to simulate the real-time behavior of an individual fire at the scale of the forest stand (Andrews 1986) or to rate daily fire danger at the scale of the national forest district (Deeming and others 1977). Even at these relatively fine spatio-temporal scales, modeling fire behavior requires making several assumptions that allow results of experiments in fire-research laboratories to be extrapolated to more heterogeneous conditions in the field. Perhaps the most critical, and frequently unsupported, of these assumptions is that fuel properties are homogeneous both in space and time (Rothermel 1972). It is a testament to the robustness of fire behavior models that, even under this weak assumption of fuel homogeneity, their performance is generally adequate at the scales at which they are currently applied (Simard 1991).

Fire-Disturbance Impacts

Processes at temporal scales longer than a day and spatial scales larger than a national forest district are poorly understood, and empirical data are generally not available at these scales (McKenzie and others 1996a). Nevertheless, there is an increasingly critical need to relate wildland fire to broader scale issues such as the potential impact of global climate change on terrestrial ecosystems (Gardner and others 1996, Ryan 1991). The composition and function of ecosystems are constrained by disturbance, and ecosystem change often occurs as abrupt transitions due to changes in disturbance regimes (Davis and Botkin 1985). Global climatic change is predicted to significantly alter disturbance patterns (Overpeck and others 1990) and thus ecosystem change could be sudden and extensive. Fire regimes may be especially sensitive to climatic change (Clark 1990), and changes in the frequency and severity of fire could be more important near-term determinants of rates of ecosystem change than more direct effects of global warming. A pulsed transfer of carbon to the atmosphere accompanying more severe fire regimes could contribute further to global warming and ecosystem instability (Neilson and King 1992, Neilson and others 1994).

Broad-scale simulation of the impact of fire will require a new approach to fire modeling that incorporates components and concepts not part of existing systems. For example, the focus at broader scales will likely shift from fire behavior and fire danger to the system-specific impacts of fire encompassed by the as yet poorly-defined concept of fire severity (Simard 1991). Unlike physical-based measures of fire behavior (e.g., rate of spread, fireline intensity, etc.) and the various indices of fire danger, broad-scale measures of fire severity would necessarily be system-specific. For example, fire severity from the standpoint of the impact on ecosystems might be measured in terms of the percent of the vegetation killed or the loss of soil nutrients, while the emissions of different gaseous and particulate species would be appropriate measures of the impact on the atmosphere. Fire occurrence would be better expressed in terms of the fire cycle or annual percent area burned, in contrast to the fire frequency and return-interval statistics that are more appropriately applied at the scale of the tree or forest stand (Johnson and Gutsell 1994). The broad-scale relationship between fire occurrence and fire severity (i.e., the fire regime) could be represented by system-specific frequency-intensity curves (Pyne 1984). As in the analysis of flood history, these curves could be used to characterize the relative severity of 10-, 20-, 50-, or 100-year events, replacing the more generalized descriptions of fire regimes (Agee 1993) that have more limited utility for long-term planning.

Fuel and Weather Heterogeneity

The relative heterogeneity of fuels and weather in space and time is a fundamental determinant of fire severity, so simplifying assumptions of homogeneity characteristic of fire modeling systems at finer levels of scale would seem inappropriate in a broad-scale fire-severity model. Greater spatial heterogeneity of fuel properties, weather, and topography generally promotes lower fire severity at landscape to regional scales. Fire severity at the stand level may be high at select positions in the landscape, but at the broader scale and under normal weather conditions, spatial heterogeneity tends to produce a low-severity regime characterized by a patchy distribution of relatively small fires (Minnich 1983, Heinselman 1985). Forces that alter spatial heterogeneity tend to alter the intensity and extent of fire. For example, timber-harvesting systems that increase the fragmentation of the landscape can reduce connectivity from the standpoint of fire spread (Green 1989, Turner and others 1989), thus decreasing average fire size. On the other hand, fire-suppression policies tend to increase both the homogeneity and flammability of landscapes and can lead to more extensive and higher intensity fire (Habeck 1985). Insects and wind can increase or reduce landscape fragmentation, depending on the scale, pattern, and intensity of the disturbance, with consequent effects on the broad-scale fire regime (Knight 1987). Fire by itself, or in concert with other agents of disturbance, can alter the level of spatial heterogeneity thus influencing the severity of subsequent events (Lotan and others 1985).

Implications for Modeling

In order to estimate broad-scale fire severity, it may not be necessary to model the impact of fire across the entire range of fire intensity and extent that occur on a landscape. The vast majority of fires, while important in the maintenance of ecosystem structure and function and the spatial heterogeneity of landscapes, may nevertheless be insignificant from the standpoint of broad-scale fire severity. Only a very low percentage of fires are, in fact, responsible for a very high percentage of the fire-caused damage to ecosystems, the atmosphere, and society (Strauss and others 1989).

Infrequent, high-intensity fires of large extent are commonly associated with a specific, synoptic-scale sequence of weather events that greatly reduces the spatial heterogeneity in fuel flammability and further increases the burn connectivity of the landscape through wind-driven enhancement of fire spread. Typically, a blocking high-pressure system with a duration of a month or more promotes extreme and extensive drying of fuels due to prolonged high temperatures, low humidity, and light winds. Partial or complete breakdown of the high pressure ridge followed by a cold-front passage or the buildup of convectional storms provides the lightning and wind that ignite and promote the spread of one or more fires through drought-conditioned, highly flammable fuels (Johnson 1992). Essentially the same relationship between the incidence of high-severity fire and this specific synoptic-scale weather sequence has been reported for systems as disparate as the boreal forests of Canada (van Wagner 1978, Payette et al. 1989, Bessie and Johnson 1995), maritime coniferous forests of the Pacific Northwest (Huff and Agee 1980, Pickford and others 1980), and ponderosa pine forests of the southwestern United States (Swetnam and Betancourt 1990).

In a broad-scale fire-severity model, the relatively infrequent occurrence of large, high-intensity fires could be predicted as a function of the duration of drought produced (Renkin and Despain 1992) by a blocking high-pressure system . The Drought Code in the Canadian Forest Fire Weather Index System (van Wagner 1987), the Keetch-Byram Drought Index (Keetch and Byram 1988), or the estimated percent moisture of the 1000-hr fuel time lag class (Ottmar and Sandberg 1985) could each serve as an index of extended drought. A threshold of the drought index together with some index of lightning activity (e.g., Price and Rind 1992, 1994) would signal the occurrence of a severe fire in the model. Behavior (e.g., surface and crown fire spread, fireline intensity, smoldering combustion) and impacts (e.g., extent and degree of vegetation damage, nutrient loss, gaseous and particulate emissions) would be modeled using existing fire spread and first-order effects models (Keane and others 1994).

In this broad-scale application of relatively fine-scale models, an adequate representation of the variation in model inputs due to landscape-scale spatial heterogeneity would be necessary to assure realistic results. One approach might be to divide the landscape up into land-surface types (Avissar and Pielke 1989, Keane and others 1995), perhaps on the basis of physiographic position, and to run the suite of fire-behavior and effects models for each distinct type, assuming within-type homogeneity of model inputs. The broad-scale severity of the event for the entire landscape could be estimated by an area-weighted average of the results for each distinct land-surface type.

It may not be necessary to model the behavior and effects of frequent, low-severity fire to the extent done for severe fire in a broad-scale fire severity model. For example, impacts on ecosystems or the atmosphere produced by low-severity fires (i.e., the majority of events) could be represented implicitly by model parameterizations that produce constant (or episodic) but relatively low levels of mortality, nutrient loss, or emissions in broad-scale simulations. These parameterizations could even be specific to different land-surface types to represent variation in frequency and intensity of relatively small-scale events across a heterogeneous landscape.

Key Questions and Responses

The key questions proposed for this workgroup (Table 3) deal with fire at large scales, in particular, (1) spatial and temporal dynamics, (2) the ecological role of fire, (3) management of fire, and (4) the critical components of the fire behavior environment. Due to the broad scope of these initial, four key questions, the workgroup felt that more specific and directed questions would better enable meaningful discussions. Therefore, the workgroup identified a total of 17 focused questions across the four key questions. Importance rankings were developed first for the four key questions, and subsequently among the focused questions within each key question. Key questions and focused questions appear below in decreasing order of importance. Responses were developed for the two or three most important focused questions under each key question. Each response was identified in terms of its characteristic scope (i.e., global to local). Those responses that were identified for a focused question were then ranked in terms of importance. No rankings were developed for feasibility aspects of any questions or responses.

1. What are the critical aspects of spatial and temporal dynamics of fire at large scales?

A. What characteristics of fire as a landscape ecosystem disturbance are relevant to large-scale (spatial and temporal) modeling? What are the characteristics of forces that drive the behavior of a fire regime?

- Fuel conditions are relevant at small and large spatial scales. (global)
- Fluctuation in climate, even at small temporal scales, will be important for modeling fire at large scales. (regional)
- Temporal variation and dynamics in fuel conditions affect large-scale fire regimes. (regional)
- Health of ecosystems is the most important determinant of disturbance at large scales. (regional)
- Vegetation structure, abundance, and distribution affect large-scale fire patterns. (biome)
- The range of variability in fire characteristics is more important than mean fire characteristics when modeling at larger scales. (global)
- Fire frequency affects large-scale fire patterns. (global)

B. What is the feedback of fires on the greenhouse effect? What is the long-term interaction of fire, ecosystem structure, and climate? What role will potential long-term temperature increases due to climate change have on fire regimes? How will fire frequency control vegetation composition with climate change?

- If climate change results in long-term increased temperatures, this will result in an increase in fires, because it will affect the availability of fuels faster than the climatological drivers of fire. (regional, especially northern latitudes)
- As ecosystems come under stress, a pulse of carbon will be released into the atmosphere due to increased numbers and severity of fires. (global)
- The relative impact of changes in fuels and climate will vary by ecosystem. (global)
- Changes in fire frequency and intensity will change vegetation composition and structure. (regional)
- An increase in fire frequency will have a negligible to slightly negative feedback effect on greenhouse gases buildup; there will be a greater effect on ecosystem health and recovery than on the release of stored carbon (increased decomposition will have a greater impact than accelerated carbon release). (forest biomes)
- Changes in fire regime will have a greater impact on ecosystems in northern latitudes relative to carbon and nutrient cycling. (regional)
- Increased fire frequency will enable conditions for life forms that can take advantage of new climatic conditions. (global)

C. How do we deal with the stochastic nature of single events in fire regimes?

D. How important are areas that are missed by fires over several events as refugia for fire-sensitive species? What is the nature of areas which are refugia; what characteristics of these areas allowed them to be missed by fire events?

E. What is the relative importance of the cumulative impact of small fires vs. the impact of rare large fires or extreme events?

F. How do we deal with heterogeneity in modeling large-scale disturbance?

2. What ecological role does fire play at larger scales?

A. What are the most important aspects of long-term changes in fire characteristics on vegetation? How is fire interrelated with other disturbance vectors? Does fire create stress in ecosystems or result from stress in ecosystems?

- Spatial patterns and distributions of species change under different fire regimes. (global)

- Changes in fire frequency, size, and intensity will change post-fire vegetation composition. (regional)
- Fire interactions with wind and insect disturbance can be as important as fire acting as the sole disturbance. (regional)
- Fire can play a role in revitalizing an ecosystem (can relieve stress); fire is more likely to occur in a stressed ecosystem. (regional)
- One disturbance can mitigate or propagate another disturbance, depending on heterogeneity in the system and the relative scale of the processes. (global)

B. How does fire (regime and individual) impact ecosystem processes and dynamics?

- Fire can affect the nutrient status and productivity of a given site. (global)
- Fire can influence site water availability. (global)
- Fire occurrence in ecosystems from which fire has been excluded can alter landscape patterns and disrupt previous ecosystem structure and functional relationships. (regional)
- Fire accelerates biogeochemical processes (e.g., carbon flux). (global)
- Fire mobilizes stored carbon (distinct from other elements which can be cycled back into the system). (global)
- Fire in a stressed ecosystem will accelerate succession. (forest biomes)
- Fire is important in maintaining a range of successional states across the landscape. (global)
- Fire may increase the rate of species response to new climatic conditions (ecosystems with long-lived species)

C. What influence does past disturbance history have in shaping current ecosystem structure (for example, looking at two drainages which share the same disturbance regime)?

3. How can fire be managed at large scales?

A. How does landscape fragmentation affect large-scale fire regimes?

- Silvicultural practices decrease the average fire size by imposing a finer scale of disturbance. (regional)
- Fire management can increase or decrease heterogeneity in the landscape. (global)
- Manipulation of fuel loading can mitigate the impacts of landscape fragmentation on fire regime; modification of fuel loading can influence fire frequency. (regional)
- Much larger fires will result from a reduction in heterogeneity; the landscape will become more and more homogeneous, resulting in an increase in fire size. (regional)

B. What characteristics of a fire regime have the most importance (provides value) to the public? (Italics are used in this list of responses to refer to labels in .)

- Fire effects on aesthetics, property, health, and safety (human) are the most important values to the public. (regional)
- Smoke production is perceived as a negative impact on visibility. (regional)
- Perceptions of fire are different depending on social, cultural, and economic factors, as well as proximity to potential burns. (regional)
- Large fires are acceptable to the public under certain situations (e.g., in parks and wilderness areas). (regional)
- The public will potentially support the concept that fire can increase safety. (subregional)

C. How should fire regimes be defined for resource management objectives?

- Appropriate fire regimes are defined by management objectives, not simply by ecosystem characteristics. (global)
- Management objectives need to be stated explicitly. (global)
- The historic fire regime should be considered in the development of resource management policy; we need to understand how systems have developed without placing value judgment. (regional)
- Managed fire regimes should not cause degradation of ecosystem components (e.g., erosion, accelerated nutrient cycling, species change). (global)
- Resource managers must understand ecological responses to different fire regimes before setting objectives. (global)

- What are the relevant landscape and large-scale issues for political boundaries (management and policy differences)?
- In a non-steady state environment, how do you chose to manage for a particular landscape?

4. What are the critical characteristics of the fire-behavior environment?

A. Under what circumstances does crowning potential become the critical aspect of fire behavior for predicting effects?

- Surface and crown fires are different disturbances with different ecological effects. (forest biomes)
- The best predictors of crown fires are different at different scales. (forest biomes)
- The mechanisms under which crown fire is propagated (threshold conditions) are poorly understood and difficult to model. (forest biomes)

B. In which environments can we assume that ignition sources are always available versus scarce?

- Ignition sources on eastside (dry) versus westside (wet) ecosystems (e.g., in the Cascade and Rocky Mountains) are different. (regional)
- Ignition sources in ecosystems with frontal versus continental climates are different. (continental)
- Flammable conditions are a necessary requirement, but the relative importance of ignition sources varies in different environments (including climatic conditions). (global)
- Ignition sources are always available at urban-wildland interfaces with high human populations. (local)
- Selected human activity can increase ignition frequency, even if human populations are low. (local)
- Process-based simulation of lightning is complex but relatively robust; statistically-based approaches may be less complex but less robust. (global)

C. How important is fire size as a feature of the fire regime?

Summary

Landscape-level changes resulting from fire are difficult to model due to climate and vegetation heterogeneity, lack of empirical data at large scales, and limited spatiotemporal scope of existing models. Nevertheless, because ecosystem composition and function change where disturbance regimes change, there is a critical need to model large-scale disturbances. Workgroup importance rankings for key questions and focused questions appear in . Due to time constraints, no feasibility comparisons were made for any of the questions, and responses were generated for only the most important focused questions under each key question.

The workgroup felt that the broad key questions proposed in the straw document (Figure 4) needed to be further refined. Focused questions were used to provide that refinement so that responses could be more easily proposed. More focused questions for “critical aspects of spatiotemporal dynamics” included: landscape-level disturbance characteristics of fire, the stochastic nature of single fire events, ecological importance of fire refugia, and the relative importance of small fire cumulative impacts versus extreme fire events. The “large-scale ecological role of fire” can be refined as: vegetation impacts, interactions with other disturbances, impacts on ecosystem processes and dynamics, and ecosystem structure resulting from past disturbance history. In order to answer “large-scale management” questions, scientists and managers need to address: landscape fragmentation effects on fire regimes, fire regime characteristics that the public values, defining fire regimes for management objectives, large-scale issues for political boundaries, and managing for a particular landscape in a non steady-state environment. The “critical characteristics of the fire-behavior environment” include: importance of crowning to fire-behavior predictions, ignition source abundance, and fire size importance to describing a fire regime. At an ecosystem and landscape level, there is much that needs to be better understood about fire as a large-scale disturbance if it is to become part of future management strategies.

FIRE-EFFECTS MODELING STRUCTURES

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Background

The effect of fire on ecosystems has been a primary concern for resource managers in the United States for over 100 years. A great deal of research has been conducted since the early 1910s to describe and understand fire-effects, but the majority of the research has been conducted at the individual tree or stand level, even though the results have been applied at larger spatial scales (McKenzie and others 1996a,b). For example, early fire suppression policies that affected thousands of hectares in the western United States were based on fire-effects research at the stand level (Fritz 1932, Schiff 1962, Show and Kotok 1923, 1924).

Resource management for the 1990s and beyond will require an understanding of ecological processes at spatial scales larger than the stand level. Accurate simulation models will be needed to predict the outcomes of complex interactions among disturbances (particularly fire), climatic changes, and large-scale vegetation patterns. A principal difficulty in building large-scale fire-effects models is the extrapolation, or aggregation problem (Cale 1995, King and others 1991, McKenzie and others 1996a, Rastetter and others 1992). In the past decade, models have been developed to predict fire ignitions, fire behavior, fire-effects, and vegetation change in response to fire (see previous sections of this document). Many of these models partially address the aggregation problem, but each type of model has identifiable sources of error when applied at broad spatial scales.

Scale issues and the aggregation problem framed the discussion and recommendations of this workgroup. Several of the key questions directly addressed scaling and aggregation error, while other more technical questions were motivated by previous difficulties in addressing these issues within models. In the following discussion, the term “fire effects” refers not only to first-order fire effects (for example, crown scorch, cambial kill, tree mortality) but also to broader scale effects (for example, altered successional pathways, vegetation mosaics, landscape dynamics).

Key Questions and Responses

The workgroup formulated 10 key questions, expanding on three of the questions in the straw document (Figure 4), and identifying seven others more directly related to modeling structures. Key questions were considered with respect to importance, but not feasibility. Workgroup members felt that key questions were too broad to enable them to make meaningful feasibility comparisons. Key questions appear below in order of priority value. As time permitted, responses to the most important key questions were ranked according to both importance *and* feasibility. Bulleted lists following each key question below enumerate responses. Key questions and their responses are listed along with rating scores in Table 4. Workgroup members agreed that all key questions are relevant to both broad (regional, national, continental, and global) and narrow (plant, stand, watershed, ecoregion) scopes. Temporal scales associated with broad vs. narrow scope were not delineated, moreover the workgroup found that questions regarding temporal issues were less precisely formulated, and less easily answered, than those regarding spatial issues.

1. How does one validate a model’s structure with respect to error propagation?

Models cannot be proven, only disproven, but confidence levels can be estimated for model outputs. Validation implies that data are available for comparison. Large amounts of data with both spatial and temporal depth are needed. Model structure affects how error propagates through a model, therefore validating a model’s structure is part of the process.

A. Need analyses of the sensitivity of a model’s internal components to both data and interactions with other models. We also need sensitivity analysis of transitions between model components at which there is spatial or temporal aggregation.

B. Compare outputs of a model and model components to independent data.

C. State the operational bounds for model inputs.

D. Compare similar models to each other and with independent data.

E. Compare model structures to structures from previously validated models. Disparate spatial and temporal scales of model application may, however, require different model structures.

2. What are the relevant spatial and temporal scale issues (including extent and resolution) related to modeling fire effects?

Fire effects occur across a wide range of spatial and temporal scales. For example, individual trees may be affected while nutrient losses occur at the watershed level, and the consequences of immediate fire effects (for example, tree mortality) are felt over decades or centuries. Thus, translating information across scales is essential in any modeling effort. Although it may not be explicitly stated, scale is implicit in all questions posed by land managers. The scale of interest dictates the modeling approach, where the model is applied, and the types of data used in model development, calibration, and validation.

A. Modeling needs to be spatially explicit and temporally dynamic. Model resolution needs to be finer than the extent desired for projection.

B. Spatial and temporal variability in weather/climate, vegetation, fuels, and fire behavior is different at different scales.

C. The appropriate temporal and spatial resolution and extent need to be determined for each modeling effort.

D. Considerations of temporal aggregations are as important as consideration of spatial aggregations.

E. The structure of fire-effects models may be different at different spatial and temporal scales.

F. Most existing data on fire effects have been collected and analyzed at small spatial and temporal scales.

G. The magnitude of the error needs to be quantified relative to the scale of implementation.

H. Models need to be designed to minimize errors at the intended scale of implementation.

3. What are the desired outputs of an "ideal" fire-effects model?

Here we are referring to first-order fire effects. The output of a fire-effects model provides information needed by other models and by researchers and policy makers. Before a useful fire-effects model can be developed, we need to know what types of information are desired by policy makers and land managers. The desired information will dictate the appropriate scale of the model and the approach that should be taken. The model should:

A. Produce spatially explicit and immediate fire-effects outputs and generate necessary inputs for successional vegetation models.

B. Include physical and biological aspects so that the model has broad applicability, i.e. process based.

C. Relate fire behavior (flaming and smoldering combustion) to fire effects. Flaming combustion is typically associated with the fire front, and smoldering combustion occurs after the fire front passes or in ground (peat) fires.

D. Produce quantitative emission characteristics and time-dependent emissions.

4. How does one calibrate a fire-effects model?

Calibration is crucial for parameterizing models so that they produce outputs consistent with observations from the real world. Calibration works in tandem with validation so that we can have confidence that a model will perform well under conditions outside the range of current experience. Often we do not have all the data needed to initialize a model, or sufficient data density to know the model is accurately representing the real world.

A. Individual components of the model should be calibrated separately.

B. To the extent possible, the model should be calibrated over the domain of the anticipated implementation.

C. Calibrate against theoretical standards, so that calibration is more than a sequence of adjustments to make the output "look right".

D. Resolution of the model should be consistent with the resolution of the data used for calibration.

E. Calibrate against a large amount of data.

F. Calibrate against another model.

5. How does scale affect the modeling approach?

The scale of the application affects the structure of the model and affects the nature of the information that one can obtain from the model.

A. As the resolution of the model changes, the approach to modeling changes (for example, from process-based to statistical). Statistical properties of aggregates are often more easily estimated and modeled than components of these aggregates (Levin 1992).

B. In the real world, the temporal and spatial scales of processes are variable. Thus aggregation error will occur when time steps and spatial resolution of different modeled processes are equalized.

6. What are the components of an "ideal" fire-effects model?

The reason for describing an "ideal" model for fire effects is to provide the context for assessing existing models. Similarly, components of an ideal fire-effects model need to be identified for comparison with components of existing fire-effects models. This will put current knowledge in perspective and identify shortcomings of current models and their components. It will also help ongoing efforts to improve our models, so that they will be useful as components of ecological modeling at multiple scales. Outputs of an ideal fire-effects model, discussed above (#3), will determine, to a great extent, the components of such a model. Responses to that question are also appropriate here.

7. What data exist for calibration, validation, and development of fire-effects models?

For years, fire research has been fragmented in time and space. Until recently, there has been little effort to maintain long-term fire-effects research. With the availability of new computing and satellite technology and associated databases, modeling fire effects at large spatial scales is more feasible. Fire-effects modelers need a rigorous methodology to compile and integrate available databases.

Most fire effects databases cover short time periods and small spatial scales. Current large scale assessment efforts (for example, the Sierra Nevada Ecosystem Project [SNEP 1996] and the Columbia River Basin Assessment [Quigley and others 1996]) present an opportunity to validate and develop new fire-effects models on larger spatial scales. The main shortcoming to date is the lack of long-term data. The sites that have been maintained (for example, Long Term Ecological Research [LTER] sites and research forests) cover relatively small areas. Much of the available data and model documentation is in the files of federal and state land management agencies.

8. What is the appropriate system structure (for example, an integrated system of separate models or a unified model)?

There are two aspects to this problem: 1) What are the ecological ramifications of linking the outputs of separate models vs. creating one model that internally integrates the abiotic and biotic processes of interest?, and 2) what are the technical and methodological tradeoffs between coupling of independent self-contained models and building a unified model from the outset?

Specific expertise possessed by modelers individually enhances the first approach (an integrated system of separate models), whereas the ability of modelers to work as a team enhances the second. The difficulty of the modeling effort is increased when the scale of desired outputs is different (usually larger) than the scale at which data are available and at which mechanistic models have been built. For example, how does the vegetation composition and spatial distribution of one model landscape change in response to a disturbance scenario, particularly fire, while retaining the fine-scale detail of fire-behavior calculations? One might "pass the ball" from a fire behavior model, to an immediate fire-effects model, to a gap-successional model, and finally to a large-scale model that uses a statistical approximation to aggregate successional model output. Or one might aggregate fire behavior inputs to the scale at which final outputs are desired, and build large-scale approximations to immediate fire effects and successional changes into a new unified model.

A. System modularity should reflect process modularity.

B. If model structure involves coupling independently developed models, internal consistency between analogous modules should be ensured and redundancy should be reduced.

C. Where possible, process-based models are preferred over statistical models.

D. The model should be structured as modular as possible.

9. How does one integrate climate into fire-effects modeling?

Fire-effects models must be sensitive to climate (weather) and climatic data must be at the appropriate spatial and temporal resolution. Models based on regressions of fire effects on empirical predictive variables are more difficult to relate to climate (weather) than are those based on theory. Theory-based models will contain explicit algorithms relating weather characteristics (temperature, precipitation, humidity, wind and lightning) to live and dead fuel amount and moisture, ignition, fire severity and fire effects on vegetation. Generating spatially explicit weather data at appropriate spatial and temporal resolutions is, however, a very difficult problem. Weather data are collected over sparse networks of weather stations and must be interpolated over complex terrain while maintaining physical consistency among the weather variables. Also, many fire-behavior models and vegetation models operate at relatively short timesteps (sub-hourly to daily) in comparison to available weather information (daily to monthly, annual or decadal). Methods must be developed and validated for interpolating raw weather data over complex terrain and from long to short timesteps.

Current tools for spatial interpolation range from geostatistical methods (for example, kriging) to regression-based methods that explicitly incorporate topography (for example, PRISM, Daly and others 1994). Perhaps the most common approach to temporal interpolation is to use statistical weather generators that maintain specific temporal autocorrelation statistics at daily, monthly, interannual, and interdecadal timescales. Combining temporal and spatial interpolation to simultaneously maintain temporal and spatial autocorrelation is an emerging technology (VEMAP participants 1995).

Spatially explicit time series of potential future climates must also be developed in order to estimate fire effects in changing climates. Perhaps the most common approach for this is to use output from General Circulation Models (GCMs). GCMs produce physically consistent weather output at timesteps of about 20-40 minutes over very coarse grids, for example, 4-5° latitude-longitude resolution. Since the grids are very coarse, the global climate is simulated over a very crude topography and does not adequately reflect the observed climate, particularly in mountainous regions. Therefore, future climatic scenarios are developed from GCMs by calculating "deltas" (ratios or differences) between simulated current and future climate. The deltas for each climate variable are then interpolated back to the baseline observed climate at the resolution of the baseline climate (VEMAP participants 1995). Such interpolation is done to carefully select and preserve temporal autocorrelation statistics produced by the GCM or existing in the baseline data.

10. What tools exist to generate data for the development of fire-effects models?

There are data gaps for many geographic areas for which we need fire-effects predictions. It is expensive and time consuming to gather relevant field data, particularly fire histories. Additionally, empirical data are often not in a form useful for modeling; there is currently a high cost associated with adaptation of field data. Most research programs have developed tools and software independently to transform field data into a format useful for modeling, thus, existing tools are in different forms and at different locations.

Summary

Recent research has produced new technologies for data analysis and integration, and quantum leaps in understanding fire as an integral process in ecosystems. We need to verify what models exist, and make their documentation available, so that we do not conduct redundant research. Most fire-effects models and data are available in university libraries in the form of theses and dissertations or in the files of federal and state land management agencies. Also, due to current societal concerns, other agencies (for example, National Aeronautics and Space Administration, Department of Energy) are incorporating fire research in their programs. Thus, improved communication among researchers in different agencies is a high priority. Electronic access to compilations of data (e.g., Fischer and others 1996) is an important first step.

We need to use the modeling process carefully to identify gaps in data, knowledge, and theory. For example, fire-effects models must be allowed to be wildly wrong. If basic model parameterization is wrong or incomplete, or if the model involves significant extrapolation across geographic areas or temporal or spatial scales, then premature calibration will mask difficulties rather than improve accuracy. However, by quantifying the calibration necessary to match observed data, we can estimate the importance of missing spatial information or the magnitude of error associated with aggregation. Thus, any model can be used to identify knowledge gaps during the process of calibration.

We need to address the scaling problem more systematically. Next to model validation, scale issues are the most important questions for fire-effects modeling structures. Although currently there are no simple solutions to the extrapolation/aggregation problem, quantifying and minimizing errors related to scale do not seem to be important issues relative to other scale issues. Both were ranked lowest by the workgroup. Spatiotemporal variability, resolution, and extent were listed both as the most important scale issues and as the most feasible. This gives them high priority for future modeling efforts.

From a strictly model-structures perspective, integrating climate into fire-effects modeling has a very low priority. Until the tools and protocols necessary for model validation, spatial and temporal scales, desired model outputs, and model calibration are provided, incorporating more realistic features into models (e.g., climatic factors) will have little impact on developing effective models. Technical knowledge of how to build the best models must precede building realistic models that include climate and other important factors.

Finally, we need to be conscious of intrinsic limits of the accuracy and precision of our knowledge, and therefore, the predictive ability of our models. For example, if events at a particular spatial or temporal scale are clearly stochastic, or governed by chaotic dynamic systems, predictive ability at those scales will be low. Judicious use of state-of-the-art aggregation techniques will be a key factor in optimizing models.

MANAGERIAL CONCERNS, APPLICATIONS, AND DECISION SUPPORT

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Background

Good management rests on a foundation of solid science. There are two challenges that must be met to properly integrate management and science. First, research and management must collaborate through research-management partnerships. The key to this relationship-building challenge is communication. Second, biological, physical, and social science knowledge must be integrated as fire-disturbance models are developed. Fire-disturbance models are the nexus of fire management and research, and need to integrate all the sciences to adequately provide the foundation for successful management of fire on the landscape.

Key Questions and Responses

After some initial discussion covering a broad range of topics, the workgroup settled on a short list of key questions. These five management and application questions are listed below, in order of importance (Table 5). For each of the key questions, lists of responses are also enumerated in order of importance. The workgroup briefly discussed narrow and broad scope topics within each key question. These are summarized within each introductory paragraph of the following sections.

Question 1: What are the most useful model structures and outputs to support issues in planning, operations, monitoring, and learning by resource managers, decision makers, policy makers, and researchers?

This question really addresses two issues—model structures and model outputs. First, model structures need to reflect the important effects and properties of fire behavior to adequately model fire-related phenomena (model realism). Second, models must provide meaningful output with diverse uses (model functionality) for a wide variety of users. This question covers many of the specific and critical integration issues between model builders and model users.

The workgroup felt that narrow-scope issues would occur at the watershed level and smaller, while broad issues would cover regions of river basin size and larger. No specific issues were enumerated at either level for this key question.

1. *Models should allow users to select fire regimes and show their probabilistic effects on the landscape.*

While fire occurrence, behavior, and effects are deterministic phenomena at a basic physical level, we are unable to reliably predict the resulting complex system of low-level interactions in terms of higher-level events. Therefore, larger-scale events that we observe appear stochastic. Spatial and temporal patterns of fire occurrence, for example, impact a number of important landscape-level features, and determine the sizes of openings, vegetation succession, and hydrologic events. But because fire regimes are uncertain in time and space, their landscape effects are also uncertain. Consequently, models should allow users to select various spatial and temporal patterns and then output different stochastic scenarios that might result from those initial conditions. Such a model would be extremely helpful to a wide variety of users, such as landscape planners, policymakers, and researchers.

2. *Data structures must be compatible with user capabilities.*

Models are only as good as the data used to drive them. It makes no sense to develop a fire-spread model that requires detailed fuels data, if those data are typically unavailable to model users. Model developers need to be cognizant of what data can be readily and reliably collected by users. Otherwise, models will be unusable, or worse, they will be used inappropriately with data for which the model was not designed.

3. *Develop hierarchical and selective modeling framework for fire regimes and fire effects (e.g., LOKI, Keane and others 1996b).*

In the past, model development and application has been highly fragmented. For the manager to accomplish a specific task, a number of different models may be needed. For example, someone wishing to plan a prescribed fire might use fire-behavior models *and* fire-effects models *and* vegetation succession models. There may be any number of different fire-effects models to choose from. An integrated, flexible, and modular framework needs to be developed so that each application task—fire behavior to fire effects to vegetation succession—flow naturally, both conceptually and operationally. As the research and technology develops, it should be possible to add new modules and update old modules. The technical complexity of the models needs to be hidden from the user behind a standard, intuitive user interface (see question #3, response #2).

4. *Provide knowledge of model limitations to users, and user needs to model builders.*

Important concepts underlying a model and model structures need to be communicated to model users. These concepts often limit what a model can do and how it should be used, and should be communicated in an easily understood way within the user documentation that accompanies the model. Limitations inherent in a model should also be incorporated into the model's user interface so that those limitations can be expressed to users and so that the interface can prevent inappropriate uses of the model. Knowledge of these intimate details of a model by users will help ensure that models are used correctly and results are interpreted properly.

Managers, planners, policy makers, and researchers need to communicate their needs to model builders as well. They need to specify to modelers the types of decisions that they make and what model output will help with those choices. As noted above, they also need to convey what types and resolutions of data they have available or are able to collect. Both of these communication channels can be most effective when they are active simultaneously as modelers design and develop models and users provide feedback on model utility.

Question 2: How do we improve communication between users and model builders (scientists), relative to the development life cycle?

The last response to the previous key question dealt with communication between model builders and model users to exchange model-critical information between them. Key question #2 more generally addresses the communication environment during the model development life cycle. This life cycle includes: planning, design, development, testing, and delivery. While there needs to be bi-directional communication all the way through this process, how do we establish an environment that fosters such collaboration? Simply put, creating such an environment can succeed only if there are active, and ongoing, efforts to do so.

Several issues of a narrow focus were identified. None of them are specific to the Pacific Northwest Region, and could easily be considered just as applicable in other contexts.

- Managers must assure the availability of researchers with needed expertise to address regional problems and questions.
- We need to account for regional issues in national research efforts.
- We must build better procedures to allow managers and scientists to participate in the decision-making process.
- In a broader focus, communication with international researchers is an important issue.

1. *Pro-actively seek opportunities to communicate.*

Many *potential* opportunities exist for model builders and model users to communicate. For example, coordinating data standards, establishing decision-making needs, setting important temporal and spatial scales, and dealing with nonpublic lands, are several issues. But little will be accomplished, unless one group or the other takes the first step. Both groups must realize that they need to seek out the other with regard to issues of mutual concern. Non project-specific gatherings, such as regional workshops, can be used to bring both sides together for informal, generic discussions and for initiating future projects. Project-specific communication, on the other hand, targets detailed issues pertaining to a singular application of concern to a particular modeling group and managerial group. In either case, both sides must feel that they can measurably gain something by actively pursuing collaboration.

2. *Build long-term relationships.*

Regional, multi-group collaborations tend to be open-ended and, therefore, long-term. However, they can suffer from a lack of specificity often associated with cooperative efforts that are not project directed. Void of a focus, interest by members in large, regional relationships can wane, unless specific targets are established for group accomplishment. Project-specific applications, on the other hand, tend to exist for a limited time because of their specialized focus. However, any significant project, no matter how specific, will often require a multi-year effort—not exactly short-term. Additionally, project-specific applications can lead to other projects, and can eventually attract other cooperators subsequently, or along the way. In a bandwagon sense, single-project collaborations can often seed future efforts beyond the scope of the initial project.

Question 3: How can we rapidly and effectively transfer research information?

Models allow us to transfer research results in a form that permits application to managerial problems. This mode of transferring research results, however, is not without complications. Research information in the form of models is encapsulated as simplifications of reality. Consequently, there need to be adjuncts, protocols, processes, and development climates to support and enhance this transfer mechanism. These things help ensure that: (1) the correct information is transferred, (2) it is transferred reliably, (3) it is applied as intended, (4) once transferred, it is relatively easy to incorporate into application, and (5) this process can occur expediently and smoothly.

Narrow-focus issues include researcher involvement in model support and in technology transfer efforts. Again, these issues are probably not unique to the Pacific Northwest Region, but cut across regional boundaries. Because this key question addresses *rapid* transfer of information, the broad-focus issue noted by the workgroup is that implementing a national information management system takes too long.

1. *Improve documentation and model support by applying product life-cycle methods.*

After the difficult tasks of model design, development, and testing are complete, an entirely new phase of the product life cycle commences. However, models developed for research environments and with research needs in mind are often scant on information about how to apply them. Extensive documentation is required to use computer models properly. Documentation can include user manuals, tutorials, on-line help facilities, bug reports, example applications, technical reports, and peer-review articles. All this helps get users started with a model, but additional and ongoing support also needs to be offered. This may include: training sessions for new users, technical support for software installation or to interface with other applications or data, programming support for bug fixes or special application needs, and model updates as new research information becomes available. Support may be made available via telephone and via the Internet. These things, of course, put a tremendous burden on developers and on an organization, so there needs to be a high level of commitment to ensure that an information infrastructure is in place to accommodate these tasks.

2. *Standardize and provide desired user interfaces.*

It is well accepted that, for most software users, the interface *is* the application. That is, when we use software applications, we think very little about how the software is reformatting a paragraph (in the case of a word-processing application) or how it is calculating a fire-spread vector for a 100 m^2 area (in the case of a fire-spread application). We are thinking, instead, about our particular problem and task and how to get the application to help us with it. In order to do that, we need to interact with a user interface that is, in effect, our sense of the application.

Therefore, an application must provide an interface (e.g., a graphical user interface [GUI]) to the user that is natural to work with—one that mirrors, in some notion, natural ways for the user to perform important tasks (Schmoldt 1992). While working with a natural and easy-to-use interface is important, it is equally important to have that same look and feel when working with other, related applications. This is essentially the idea developed and marketed by Apple Computer, Inc. in the 1980s, and subsequently adopted by most other developers of computer operating systems since. When all applications present a consistent interface to users, the time required for users to become proficient with a new application is reduced drastically. Neither of these considerations is critical for transferring research information, but without them results will be more awkward for users and are less likely to be adopted and applied.

3. *Explore alternate means for accomplishing data management (e.g., contracting.) and technology transfer.*

Information-resources management requires tremendous organizational commitment, both funding and infrastructure. Such levels of organizational support do not appear overnight; they require time to evolve and develop. Also, supported information resources may not meet the needs of all users. In certain cases, users' needs may be unique and may not be readily satisfied given the current or planned organizational information resources.

These limitations of existing information-resources management mean that other avenues may need to be investigated to meet users' needs. For example, in some cases it may be more expedient to contract for data collection or for data management, rather than assume large amounts of overhead to accomplish the same tasks in-house. In other cases, model development and support may be more readily handled by the private sector where the necessary resources and expertise already exist. Alternative means to accomplish data management and technology transfer should be considered before investing large amounts of internal resources.

4. *Establish and support a development group.*

It has already been suggested above that model builders and model users work closely together to build long-term relationships. One particular form of long-term relationship is a development group. Rather than working solely on a singular project of moderate-to-long duration, as noted above, a development group can be formed to work on multiple projects as part of an ongoing relationship.

This development group can be formally described and funded or can assume a more informal collaboration in which only tasks and outcomes are well-established. The bond created as part of a development group provides security and stability for both developers and users. Developers know that their efforts will be accepted, applied, and appreciated, because models are designed with users' needs in mind. Users are secure in the knowledge that they will get help with their immediate managerial problem and have the support of a group that they can consult as future needs arise.

5. *Apply free market principles (product development, support, and distribution).*

Marketing principles, as applied in the business world, can be borrowed and instituted for developing, supporting, and distributing fire-disturbance models. Product markets have their genesis in a perceived user need. A product developed for *this* market attempts to fill *that* need, and to be attractive to users, it must be distinguishable from other, similar products—distinction can be due to lower price or a higher quality product or service. This means, first, that model builders must understand the model users' needs and must adapt models to managerial application. Secondly, their model must do something different or better than other competing models.

One way to distinguish one model from another is through the model support that is offered. As noted elsewhere throughout this section, a good model (or marketable product) will fall into disuse or will disappoint users if it is not supported. Follow-up service needs to target users' questions and problems, including installation, use, application, extension, and integration. Models that perform well in this arena will be applied widely and will establish themselves as valid and essential managerial tools.

Distributing a model effectively requires, among other things, knowledge of potential users and their applications (i.e., the decisions that they must make). Of course, this information is essential during the model development stage as well. Advocacy, or testimonial, by a satisfied user is one way that businesses sell a product or service. This approach can be applied here also. By working closely with an end-user through model development and by supporting delivery and application, that user will become an advocate for that model to other users. Model developers can also target those professional meetings that cater to managerial concerns and applications. Demonstrations and workshops can also be used to introduce a model to the user community. If actual use and application of a model are important to a developer (which they should be), then some effort must be directed to promoting and distributing a model much like a business concern would sell a product.

Question 4: How can we incorporate social and political issues into models and decision-support systems?

One of the cornerstones of the ecosystem management paradigm is the inclusion of social and political issues into land management. From a practical standpoint, this is not a new idea—social and political concerns have influenced land management for a long time. What is new is that social and political issues must now be validated and explicit, and must be considered in concert with biological and physical components of the landscape. Human interactions are now part of the landscape's ecology rather than exogenous to the biophysical system. Consequently, models and decision-support tools must have mechanisms that incorporate or consider social and political issues.

At the state level, models should be useful in supporting state regulations. At the national level, it should be possible to incorporate congressional and agency policy into models. Also at the national level, there should be compatibility and comparability of analysis outputs across regions.

1. *Incorporate sociological research when developing decision-support systems.*

Recent and extensive sociological research is beginning to understand and explain many of the cultural, political, and economic impacts of human populations. These impacts have modified landscape use and appearance over time and will continue to do so. As fire-disturbance models deal with large spatial and temporal scales, there is a need to include timely sociological research into models to account for human influences and land use. Otherwise, a very significant determinant of landscape change is ignored by those models. Not only direct human impacts on the landscape should be considered, but also public preferences and perceptions regarding fire. For example, human understanding and tolerance for fire disturbances and effects might be included in models that deal with suppression, fuels management, smoke management, or prescribed burning.

2. *Modelers and managers must be aware of emerging issues and anticipate future concerns.*

In addition to current social issues and their influences on modeling and decision support, there needs to be awareness of emerging issues—changes in the way that the human population interacts with the natural environment. Public interests, demands, and perceptions change much more often and unpredictably than biophysical phenomena. It is important to anticipate those changes where possible and react quickly and intelligently to them. In the future, there will be new social issues of which we are not currently aware, and with which we are currently unable to assess from a modeling perspective. Based on recent sociological trends, however, we should develop models that can adjust to social changes, much like current fire-behavior models can be modified to deal with a variety of fuel conditions.

Question 5: How can relevant interdisciplinary resource management issues be incorporated into models?

The previous question dealing with social concerns is closely tied to ecosystem management, and hence it received special treatment. However, it can also be viewed as a special case of the general question that deals with incorporating interdisciplinary resource-management issues into models. That is, how can we incorporate issues from diverse resources, such as wildlife, soils, water, timber, fisheries, and recreation, into our large-scale fire-disturbance models? There are few specific answers that the workgroup can offer to this question. Exact details will vary from instance to instance. However, the following responses provide general guidance on how to address interdisciplinary issues.

A number of resource issues specific to the Pacific Northwest were mentioned by the workgroup as important. These are:

- Interaction of fire with threatened and endangered species of regional concern (e.g., northern spotted owl)
- Protection of coarse woody debris in streams and rivers
- Old-growth sustainability
- Air quality with respect to human health
- Class 1 wilderness area visibility
- State smoke management plans
- Water quality
- Broader issues of concern to the workgroup are: (1) interaction of fire with threatened and endangered species, (2) regional haze generation and mitigation, and (3) fire impacts to carbon balance.

1. *Open communication between modelers and users.*

The frequency with which the idea of communication has been reiterated throughout this workgroup report attests to its importance. Modelers and users must communicate *openly* about interdisciplinary issues—data available for various resources, influence on and by fire disturbance, and managerial decisionmaking needs. Not all interdisciplinary issues have equal importance or good data availability. Modelers should select those interdisciplinary issues that have high importance for managers *and* for which good data exist.

2. *Involve a cross-section of managers and policymakers in model development.*

It is obvious that the interdisciplinary nature of resource-management issues demands that a cross-section of resource managers be involved. This ensures that each discipline is included adequately, and that cross-cutting issues are properly addressed by knowledgeable representatives from each subject area. Because decisionmaking needs of policymakers differ from managers, both types of disciplinary specialists should be included.

3. *Assign responsibility, develop measurement criteria, monitor accomplishments, and provide accountability for both research and management.*

There are a number of fairly specific things that can be done to help incorporate interdisciplinary issues in models. First, responsibilities for data collection or issue identification and description should be assigned to someone. Second, measurement criteria should be defined to establish what aspects of, and to what extent, a discipline is incorporated into a model. Third, research and management should periodically monitor accomplishments to determine whether work is progressing satisfactorily. Fourth, both developers and users should be accountable for their tasks and for the overall capabilities and application of the model. Because of the number of different specialties involved with an interdisciplinary modeling project, it is particularly important that everyone have clearly defined and monitored tasks with well-established metrics for success.

Summary

In general, the needs addressed by this workgroup include building "better" models (more accurate, more inclusive, more useful), integrating models into decision-support tools, improving communication, and strengthening relationships between management and research. Models need to have increased flexibility to cover a broad range of vegetation, fuels, climate, and topography. They also need to include more aspects of fire behavior, such as lightning strikes, crown-fire ignition, and crown-fire spread. In order to assist with decision support, modelers and users must communicate effectively in order to develop joint models that address current management issues, such as social and political needs and biodiversity concerns.

Analytical Methods and Results

Analysis of Priority Vectors

Pairwise comparisons by workgroup members allowed us to generate priority vectors for the items being compared, using the principal right eigenvector method of Saaty (1980). These priorities may be for either "importance" or for "practicality/feasibility/doability". Within a workgroup, all corresponding judgments by workgroup members were geometrically averaged to produce a single judgment for each comparison. This produced a group priority vector. But there were two questions that could be asked about the final priority vectors. One, is there general agreement among workgroup members with respect to the rankings in the priority vector? Two, are different priority values in a priority vector really different? Answers to these questions would have a significant bearing on how the final rankings would be used to direct research on large-scale fire-disturbance modeling.

The individual judgments used to create a group priority vector can be treated as samples from a population of experts that are independent and identically distributed. Then, separate priority vectors can be generated from the judgments of each workgroup member separately. The resulting sample of priority vectors can then be analyzed statistically to answer the above questions.

Individual judgments are taken from the set [1, 2, ..., 9] and their reciprocals. We can assume that this constitutes a truncated log-normal distribution (Basak 1990, Crawford and Williams 1985, de Jong 1984), or some other distribution, e.g. gamma (Vargas 1982, Zahedi 1986), and then perform the necessary calculations to determine the distribution of the principal right eigenvector, which is the priority vector. However, this locks in assumptions about the distribution of individual judgments and can result in very complicated statistical tests. Alternatively, we can assume that final priority vector elements are distributed normally and perform an analysis of variance with post-hoc tests for mean differences. However, one would not necessarily expect vector elements to be normally distributed and, in fact, with the small sample size, normality tests are not very convincing. The third alternative, and the one chosen here and used by Smith and others (1995), is to conservatively apply distribution-free tests that are analogous to tests based on the normal distribution of vector elements. The drawback is that distribution-free tests are conservative and may fail to detect significant differences.

Each of the following three tests ranks the data prior to calculating statistics, so relative magnitude information is lost (SYSTAT 1992). This constitutes the conservative nature of these tests. The Friedman two-way analysis of variance test analyzes the rankings by the different workgroup members for each set of items (key questions or response, in our case) being compared. The null hypothesis is that there is no systematic variation in the rankings across items by workgroup members. The Kruskal-Wallis one-way analysis of variance test indicates whether there are differences between the priority vector elements (i.e., key questions or responses) taking into account all workgroup member judgments. The null hypothesis is that there are no differences. While this test identifies that differences exist, it does not specify which vector elements are different.

The Wilcoxon signed-ranks test indicates which pairs of priority vector elements are different. A pairwise table of probability values can be created that is equivalent to an ANOVA post-hoc test for mean differences. However, this test may not provide us with conclusive results in all cases. This occurs for three reasons: (1) the Kruskal-Wallis test calculates probability values based on a Chi-square approximation, and the Wilcoxon signed-ranks test uses a normal approximation—so while the former may indicate a statistically significant result, the latter may not confirm any differences in the pair-wise tests, (2) some mathematical precision is lost because ranks are used rather than actual data values, and (3) poor agreement on rankings by workgroup members will mask differences between individual responses. Nevertheless, results from these conservative statistical tests can discern some important differences in rankings. Analyses and conclusions for each of the workgroups appear in the following sections.

Linkages Among Fire Effects, Fuels, and Climate

Analysis of Rankings

The following analyses examine rankings of importance for the key questions and of importance and practicality for the responses to each key question. For each type of ranking (importance or practicality), we applied the distribution-free statistical tests described previously to: (1) determine how well workgroup members agree on their rankings of key questions or responses, (2) determine whether there are significant differences between rating scores for the key questions or responses, and (3) identify which key questions or responses differ significantly. The next sections analyze importance and practicality separately.

Importance Rankings

Key Questions

Six workgroup members compared the five key questions appearing in Table 2 with regard to importance. A Friedman two-way analysis of variance test rejects the null hypothesis ($p = 0.001$), indicating that workgroup members' judgments vary in a systematic way. That is, there is good agreement on the rankings of key question importance across workgroup members. A Kruskal-Wallis test for differences of mean rating scores for the key questions is also highly significant ($p < 0.0005$) suggesting that real differences exist between the rating scores. A Wilcoxon signed-ranks test produces a matrix of pair-wise probabilities (Table 6) that indicates which of the key question importance scores in Table 2 may actually be different. The highest ranked key question (*factors* [.38]) is significantly more important than each of the other key questions, while the second highest ranked question (*knowledge* [.25]) is different from the two lowest-ranked key questions. There does not seem to be any evidence to suggest that the two lowest-ranked key questions (*mgmt import* [.08] and *landscape* [.11]) are significantly different. This produces a three-level scale of importance for these key questions—with one question at the top, two at the bottom, and two questions lying between the others.

Responses

The number of responses varied with each key question. Also, for question #3, dealing with scales, only five workgroup members were able to provide judgments. Statistical tests, similar to those conducted for the key questions, were performed for each set of responses. Results for the Friedman and the Kruskal-Wallis tests applied to the responses of each key question appear in Table 7. Only for the *landscape* key questions is there evidence to indicate good agreement by workgroup members regarding rankings of the respective responses. Lack of agreement for the responses to the other three key questions obscures individual response differences detected by subsequent tests. Still, for *mgmt import* and *landscape* key questions there seem to be significant differences between rating scores for the different responses, as indicated by the Kruskal-Wallis test probability values.

Despite the conservative and approximate nature of these tests, a few differences are apparent from the probability matrices in Tables 6-7. The highest-ranked response (*know fire* [.16]) for key question #2 (Table 8) appears to rate significantly more important than the lowest three responses, but otherwise there is little statistical evidence to say that the workgroup was able to distinguish differences among these responses. No significant differences were detected between the responses to question #3, owing most likely to the lack of agreement by workgroup members, as is apparent from Table 7. On the other hand, workgroup judgments were very consistent for key question #4 (Table 9). For this question, the highest-ranked response (*engineer* [.28]) differs from the four lowest-ranked responses. With regard to management linkages, key question #5, the two highest-ranked responses (*public* [.17] and *know mgmt* [.17]) differ from the three lowest-ranked responses (Table 10). Again, it should be emphasized that lack of agreement on judgments by workgroup members for each set of responses led to importance ratings with a fairly narrow spread after averaging. This resulted in few significant differences across ratings for each set of responses.

Practicality Rankings

As noted above, the key questions were not compared with respect to doability, and no comparisons were made for the responses to question #1. All six workgroup members compared the responses to questions #2-4, but only four members were able to make doability comparisons for key question #5. Statistical tests, similar to those conducted for the key question responses with respect to importance, were performed. Results for the Friedman and Kruskal-Wallis tests appear in Table 11. Only for the *mgmt import* key question is there strong evidence to indicate good agreement by workgroup members regarding rankings of the responses (Friedman test). There is also reasonably good agreement for the *scales* key question (0.083). For those same two key questions, there appear to be significant differences between rating scores for the different responses, as indicated by Kruskal-Wallis test probability values.

There are no apparent differences between responses to key question #2, due in large part to the lack of agreement by workgroup members. When we examine the Wilcoxon signed-ranks test for *scale*, the highest-ranked response seems to be different than the three lowest-ranked responses at $p = 0.68$ (Table 12). For question #4, the highest-ranked response for doability, *adjacency*, appears different from two of the lower-ranked responses, *fire regime* and *fire breaks* (Table 13). Additional differences, however, are masked by low consistency scores. In the *mgmt import* key question the workgroup felt that the two highest-ranked responses, *public* and *know. mgmt*, are much more doable than any of the other responses (Table 14). This strong result reflects the high level of consistency in workgroup judgments that is statistically highlighted in Table 11.

Conclusions

Knowing the *factors* important to fire disturbance and *knowledge* about linkages between them seem to be substantially more important than the other key questions (Table 6). Key question #5, "linkages important for management", on the other hand, is the least important—owing perhaps to the current lack of fundamental scientific knowledge about the important factors and their linkages. That is, because the science contains large gaps, management issues cannot be intelligently addressed and, hence, are secondary.

Aside from particular exceptions noted in the pages above, responses within each key question were difficult to rank according to importance or doability. This is most likely due to the number of items being ranked (7 or 9 in each case) and to the relative lack of consistency among workgroup members' judgments (Tables 7 and 11). While each workgroup member's judgments were internally consistent, there was little agreement between members. This level of non-agreement strongly corroborates the feeling that our current knowledge about linkages among fire effects, fuels, and climate is poorly understood and should be an important focus for future research and expanded modeling efforts.

Fire As a Large-Scale Disturbance

Analysis of Rankings

The following analyses examine rankings of *importance* for the key questions, for the focused questions under each key question, and for the responses to selected focused questions. In each case, we applied the distribution-free statistical tests described previously to: (1) determine how well workgroup members agree on their rankings of questions or responses, (2) determine whether there are significant differences between rating scores for the questions or responses, and (3) identify which questions or responses differ significantly. The next sections analyze importance for the key questions, the focused questions, and the responses, separately.

Key Questions

Five workgroup members compared the four key questions appearing in Table 3 with regard to importance. A Friedman two-way analysis of variance test fails to reject the null hypothesis (p = 0.115), indicating that workgroup members' judgments may not vary in a systematic way. That is, there is no statistical evidence to say that good agreement exists for the rankings of key question importance across workgroup members. Despite this lack of significant agreement, however, a Kruskal-Wallis test for differences of mean rating scores for the key questions is significant (p = 0.052), suggesting that real differences exist between the rating scores for the different key questions. A Wilcoxon signed-ranks test produces a matrix of pair-wise probabilities (Table 15) that indicates which of the key question importance scores in Table 3 may actually be different. There is some statistical evidence to suggest that the highest ranked key question (*dynamics* [.41]) is significantly more important than the two lowest-ranked key questions (p = 0.068 in each case). The second ranked key question (*ecological* [.28]) falls in between the others and cannot be distinguished as significantly different from any of the other key questions.

Focused Questions

The number of focused questions varied with each key question. Statistical tests, similar to those conducted for the key questions, were performed for each set of focused questions. Results for the Friedman and the Kruskal-Wallis tests applied to the focused questions of each key question appear in Table 16. Only for the *dynamics* key question is there any evidence to indicate some agreement by workgroup members regarding rankings of the focused questions (p = 0.074). Lack of agreement on the focused questions of the other three key questions obscures individual response differences that could be detected by subsequent tests. For the *dynamics* key question there appears to be a significant difference between rating scores for the different focused questions, as indicated by Kruskal-Wallis test probability value (p = 0.041).

Due to the lack of workgroup agreement on rankings, no significant differences could be identified among the focused questions for key questions #2 and #4. The most consistent rankings occurred for the focused questions in key question #1. Pair-wise probability values for mean differences appear in Table 17. Here, the lowest-ranked focused question *stochastic* appears to be significantly different from the remaining ones, except *refugia*, which is the second lowest one. In key question #3, the highest-ranked focused question *fragmentation* appears to be different from the two lowest-ranked questions *political* and *landscape* (Table 18).

Responses

It is apparent that there is little agreement among workgroup members regarding the importance of responses to the most important focused questions (Table 19). Only for the second focused question *public* under the *managed* key question was there good agreement and were differences between response ratings significant. The highest-ranked response *aesthetics* appears different (Table 20) than all the other responses, except *perceptions*, the second-highest response. Similarly, the lowest-ranked response *safety* appears relatively different from the two, highest-ranked responses. No other differences are significant.

Conclusions

Although the workgroup offers few consentaneous and specific recommendations regarding research on fire as a large-scale disturbance, we suggest that the most important first step is to develop higher resolution methods of assessing temporal and spatial dynamics. This can initially be accomplished through the improvement of existing fire-effects models. The large number of questions secondary to the initial key questions suggests that there are many facets to assessing large-scale fire-disturbance effects. The temporal and spatial dynamics of large fires are mostly unknown, particularly as they relate to fire behavior in complex topography. This clearly limits our ability to understand the ecological effects of large fires and to deal with them from a managerial perspective.

Fire-Effects Modeling Structures

Analysis of Rankings

To ease the task of making comparisons, the workgroup logically divided the 10 key questions into 2 subcategories, one addressing model structure and application issues and the other, model data collection and use. Key questions within each subcategory were compared pair-wise with regard to importance only, and then the two subcategories, themselves, were compared for importance. Then, multiplying the priority values for each key question in each subcategory by the priority values of its subcategory produced global priority values for the key questions. As in the other primary topics, distribution-free statistical tests were used to discern differences in rankings and to identify where workgroup members agreed in their rankings.

Importance Rankings

Key Questions

Table 4 lists aggregated ratings for the key questions and responses. We performed a Friedman two-way analysis of variance test to discern differences in rankings for the key questions across the six workgroup members. The Friedman test rejects the null hypothesis ($p = 0.002$), indicating that workgroup members' judgments vary in a systematic way. That is, there is good agreement on the rankings across workgroup members. A Kruskal-Wallis test for differences of mean rating scores for the key questions is also highly significant ($p = 0.001$) suggesting that real differences exist between the rating scores for the different key questions. A Wilcoxon signed-ranks test produces a matrix of pair-wise probabilities (Table 21) that indicates which of the key question importance scores in Table 4 may actually be different.

The highest ranked key question *validation* seems to be significantly more important than most of the remaining key questions. It is not different, however, from the next two highest ranked key questions, *scale issues* and *model outputs*. Similarly, the second highest ranked key question *scale issues* is significantly different from the six, lowest ranked key questions. Although the third highest ranked key question *model outputs* has a relatively high aggregate score (0.14), significant differences with lower scores are not substantiated due to the highly variable ratings for that key question by workgroup members. For many of the remaining key questions few patterns of significant difference can be claimed. While overall agreement in rankings is supported by the Friedman test, there are instances where excessive variation in ratings (and rankings) obfuscates more meaningful results.

Responses

Responses were generated for six of the ten key questions as workshop time allowed. Five of these six constitute the most important questions. A statistical examination of workgroup member ratings of responses within each key question appears in Table 22. There is good agreement (Friedman test) by workgroup members with respect to response rankings for three of the six key questions, including the two most important ones from Table 4, *validation* and *scale issues*. For each of these three key questions where agreement is high, Kruskal-Wallis tests for mean differences in rating scores for the responses are also very significant. For the other key questions where there is less agreement among workgroup members, mean differences are less statistically significant.

Wilcoxon signed-ranks tests provide details about specific differences between response ratings for the key questions. We only look at those key questions where workgroup members had good agreement in rankings (from Table 22). For key question #1 *validation*, we find that the lowest ranked response *bounds* is very different from each of the other responses (Table 23). The second lowest ranked response *compare to models* is different from the two highest ranked responses and from the lowest one. The two highest ranked responses *sensitivity* and *compare to data* are both different from the two lowest ranked responses. So, for this key question there seems to be a definite, high-importance group of two responses and a low-importance response, and then two responses that fall in the middle somewhere.

For key question #2 *scale issues*, there are few really strong differences between responses (Table 24) due to their number (8) and their relatively similar magnitudes. The lowest ranked response *minimize errors* is different from most other responses. The highest ranked response *fine resolution* is different from many of the lowest ranked responses, but surprisingly, not from the second lowest ranked one *quantify error*. For key question #5 *scale effects*, the two responses are different at the $p = 0.038$ significance level.

Feasibility Rankings

Only *responses* to key questions were rated with respect to feasibility. For the six key questions listed in Table 25 only two, *scale issues* and *calibration*, had significant ($p < 0.05$) Friedman test values, indicating workgroup agreement on rankings. Even though the Kruskal-Wallis test for key question #1, *validation*, produces a relatively significant probability score, the lack of agreement across workgroup members causes most pair-wise Wilcoxon signed-ranks tests to be not significant. Consequently, a table of those values is not provided here.

For the responses to key questions #2, *scale issues*, the least important response is also the least feasible, and seems to be significantly less feasible (Table 26) than most of the other responses. The two most feasible responses, *variability* and *resolution and extent*, are significantly different from the three least feasible ones. However, because the feasibility ratings in Table 4 do not vary drastically for this key question, few of the other responses can be judged as different from either the most or least feasible responses. For key question #4, *calibration*, the most important response, *components*, is also the most feasible, and there is some statistical evidence to suggest that the feasibility rating score for *components* is different from the three least feasible responses (Table 27). One of the least feasible responses, *domain*, seems to be different from several of the more feasible responses. Because the Kruskal-Wallis test was not highly significant ($p = 0.06$) for key question #4, there are few specific differences that can be teased from the results.

Conclusions

At the level of key questions, workgroup members were very consistent in their rankings of importance. Due to the broad nature of the key questions and the many tasks needed to address them, however, workgroup members felt ill-equipped to provide reasonable judgments about feasibility for the key questions. Key questions dealing with "validating a model's structure" and "incorporating relevant spatial and temporal scales for fire effects" received high importance rankings by the workgroup as a whole. There is also good agreement by the workgroup on the relative importance of responses to these two key questions, and some significant differences between the highest and lowest ranked responses are apparent. Combining importance rankings and feasibility rankings for responses to the second most important key question seems to indicate that the second and third most important responses (*variability* and *resolution and extent*) are also deemed quite feasible. This has important implications for research program direction.

While statistical significance among all the workgroup's rankings provides some assurance of real differences, the distribution-free tests used are approximate and conservative. Consequently, other less obvious numerical differences should not necessarily be ignored or dismissed.

Managerial Concerns, Applications and Decision Support

Analysis of Rankings

The following analyses examine rankings of both importance and practicality for the key questions and for the responses to each key question. For each type of ranking (importance or practicality), we applied the distribution-free statistical tests described previously to: (1) determine how well workgroup members agree on their rankings of key questions or responses, (2) determine whether there are significant differences between rating scores for the key questions or responses, and (3) identify which key questions or responses are significantly different. The next sections analyze importance and practicality separately.

Importance Rankings

<u>Key Questions</u>

Six workgroup members compared the five key questions appearing in Table 5. A Friedman two-way analysis of variance test rejects the null hypothesis ($p < 0.0005$), indicating that workgroup members' judgments vary in a systematic way. That is, there is good agreement on the rankings across workgroup members. A Kruskal-Wallis test for differences of mean rating scores for the key questions is also highly significant ($p < 0.0005$) suggesting that real differences exist between the rating scores. A Wilcoxon signed-ranks test produces a matrix of pair-wise probabilities (Table 28) that indicates which of the key question importance scores in Table 5 may actually be different. There does not seem to be any evidence to suggest that the two highest-ranked key questions (*model structures* [.43] and *communication* [.28]) are significantly different. These two key questions do differ significantly, however, from the other three questions. The third highest-ranked key question (*information transfer* [.15]) also appears to be significantly different from the two lowest-ranked questions (*relevance* [.06] and *social/political* [.07]). Consequently, there seem to be three significant levels of importance for these key questions—with two questions at the top, two at the bottom, and the fifth question lying between the others.

<u>Responses</u>

The number of responses varied with each key question. Again, however, six workgroup members compared responses for each question. Statistical tests, similar to those conducted for the key questions, were performed. Results for the Friedman and Kruskal-Wallis tests applied to the responses of each key question appear in Table 29. Only for the most important and least important key questions is there evidence to indicate good agreement by workgroup members regarding rankings of the respective responses. Lack of agreement for the responses to the other three key questions obscures any individual response differences detected by the subsequent tests. However, for each key question there seem to be significant differences between rating scores for the different responses, as indicated by Kruskal-Wallis test probability values.

Despite the conservative and approximate nature of these tests, a few differences are apparent from the probability matrices in Tables 30-32. The highest-ranked response for key question #1 *fire regimes* appears to rate significantly different than the other three responses (Table 30). While Kruskal-Wallis tests for key questions #2 and #4 (each key question having only two responses) show a significant difference between their respective responses, Wilcoxon signed ranks tests for differences of means fails to be significant—owing most likely to the different approximations that the two tests employ. For key question #3, the judgments were not entirely consistent across workgroup members (Talbe 29), so although overall means for each response showed significant differences, individual comparisons were less significant (Table 31) because counts of rank differences were mixed. Judgments for responses to key question #5 (the least important one) were highly consistent. This allowed any rating differences to be easily picked up by the other tests despite the conservative and approximate nature of those tests. All three responses appear to be significantly different from each other (Table 32).

Practicality Rankings

<u>Key Questions</u>

For practicality comparisons, only five workgroup members analyzed the five key questions appearing in Table 5. A Friedman two-way analysis of variance test marginally rejects the null hypothesis (p = 0.057), indicating that workgroup members tend to agree on their rankings. A Kruskal-Wallis test for differences of mean rating scores for key-question practicality is significant (p =0.017), suggesting that real differences exist between the rating scores. A Wilcoxon signed-ranks test produces a matrix of pairwise probabilities (Table 33) that indicates which of the practicality scores inTable 5 may actually be different. The highest-ranked key question for practicality (*communication* [.44]) is significantly different from the two-lowest-ranked questions (*relevance* [.13] and *social/political* [.06]). The second highest-ranked key question (*information transfer* [.17]) is slightly above the $\alpha = .05$ threshold of significance (p = 0.068), indicating difference from the lowest-ranked key question (*sociopolitical* [.06]). Otherwise, there are no other discernible differences between key questions with regard to practicality.

<u>Responses</u>

Again, five workgroup members compared responses for each key question with respect to practicality. Statistical tests, similar to those conducted for the key question responses with respect to importance, were performed for practicality. Results for the Friedman and Kruskal-Wallis tests appear in Table 34. Only for the most practical key question is there evidence to indicate good agreement by workgroup members regarding rankings of the responses (Friedman test). For three of the key questions, there do not appear to be significant differences between rating scores for the different responses, as indicated by Kruskal-Wallis test probability values.

When we examine the Wilcoxon signed-rank test for *communication* (the most practical key question), the two responses seem to be very different, with “pro-actively seek opportunities to communicate” being a much more practical response than “build long-term relationships” (Table 35). The only other key question that contains any significantly different responses appears to be #3, *information transfer*. For this key question there is some evidence (Table 36) to suggest that “free market principles” is much less practical than “standardize interfaces” and “explore other means for data management and tech transfer.” No other significant differences are apparent for responses to these two key questions.

Conclusions

Useful model structures and output to support decision-making are the most important issues for fire management. Improving communication between users and model builders also appears to be a critical issue for management, applications, and decision support. There was relatively good agreement that pro-actively seeking opportunities to communicate is more important *and* more practical than building long-term relationships. For the development and application of fire models, pro-active communication is an issue that can be readily addressed. It also is the most practical and cost-effective approach to ensuring that models will meet the needs of the fire management community. Combined high scores for importance *and* practicality make *communication* a key factor for the application of large-scale fire-disturbance models to management and decision support.

In general, there is much less agreement by workgroup members on the practicality of key questions and, in particular, the practicality of responses to various key questions. This probably reflects a better understanding by the workgroup of what things are important to managers and policymakers, and less understanding of which things can be accomplished most practically.

ADDRESSING FIRE-DISTURBANCE ISSUES: WORKSHOP RESULTS AND APPLICATIONS

The structured workshop process proved to be an effective way to develop issues, information, and approaches for addressing fire-disturbance effects on ecosystems. Application of this process and use of the straw document (Table 2) varied among workgroups, but the availability of a prescribed process and conceptual template greatly facilitated timely discussion of topics and quantification of priorities. We observed that resource managers in the workshop appeared to adapt to the structured approach more readily than the scientists, a phenomenon we have observed in other workshops and settings as well (e.g., Peterson and others 1994).

The priority research issues developed by each workgroup tended to be quite general, suggesting that we currently lack some of the basic information necessary to accurately assess and predict the effects of large-scale fire disturbance on natural resources. This is perhaps not surprising, because the vast majority of fire-effects research has been conducted at small scales, making it difficult to extrapolate upward to much larger scales (McKenzie and others 1996a). The ranked judgments of workshop participants provide a strategic approach for addressing priority research questions, with guidance for specific research approaches that will lead to timely answers for the scientific and resource management communities.

Individual workgroup members were internally consistent in their judgments about priority questions and responses, although experts within a workgroup sometimes differed considerably in their priority ratings. The average judgments for each workgroup were also highly consistent. The workgroup dealing with linkages between fire effects, fuels, and climate and the workgroup addressing fire as a large-scale disturbance had lower agreement on rankings than the other two groups. This may reflect both the uncertainty associated with the former two topics (science questions), as well as the more applied nature of the latter two topics (model development and technology transfer).

We can infer a rather straightforward message from the highest-ranked question (What, where, and when are key factors related to fire disturbance?) and the large amount of information generated by the workgroup focusing on linkages among fire effects, fuels, and climate: we have relatively little information about interactions among physical and biological environmental characteristics relevant to large-scale fire. Furthermore, we have few data on fire phenomena which can be readily applied to large-scale fires or extrapolated from small scales to large scales. This leaves scientists and managers with two alternatives. We can initiate an intensive data collection effort with emphasis on large-scale fire, or we can develop or improve models that use existing data and concepts to predict fire effects. Some mixture of these strategies would be ideal, but given that it is unrealistic that there will be sufficient funding for a major data collection effort, it is more effective, at least in the short term, to improve the accuracy of existing models that can make predictions at large spatial scales.

A related theme was discussed in great detail by the workgroup on large-scale fire effects, whose highest-ranked question (What are the critical aspects of spatial and temporal dynamics of fire at large scales?) emphasizes the dynamic nature of large-scale fire phenomena. It was noted that there are few data available on fuels and vegetation structure at large spatial scales, and that interactions of fuels and vegetation may be quite different at large scales than at small scales. Even if better quantitative information is available on climate-fire-vegetation interactions, it will be difficult to predict fire occurrence and subsequent effects because of the complex and stochastic nature of these interactions over time. Additional basic information on large-scale fire dynamics is needed to provide the basis for more scientifically-supported fire management at large spatial scales and over many decades.

Because it is unlikely that substantial quantities of new data at large spatial and temporal scales will be collected in the near future, scientists and managers are increasingly turning to models to assist in understanding ecosystem responses and to predict the impacts of fire on natural resources. The highest-ranked research question for the workgroup on fire-effects modeling (How does one validate models with respect to error propagation?) reflects concern about problems associated with extrapolating fire-effects data and quantitative relationships from small to large scales. It was emphasized that the most useful models will be those that are both spatially explicit and temporally dynamic, and that the structure of fire-effects models may differ at different spatial and temporal scales. At the present time, it is more efficient and cost-effective to modify and develop linkages for existing models, rather than to build new models. Scientists and resource managers need to find ways to incorporate empirical data in models to improve their predictive capability.

Resource managers appear ready to apply and integrate fire-effects models in their fire-management programs, provided that those models have demonstrated good predictive capability. The highest-ranked question for the workgroup on managerial concerns, applications, and decision support (What are the most useful fire-effects model structures?) indicates that resource managers are looking to scientists for guidance on the best models for specific management applications. It is clear that managers would like to use a hands-on approach to modeling, which allows them to select fire regimes and management options in order to simulate their effects on natural resource outputs and interactions. Therefore, effective user interfaces will be critical for successful communication and transfer of information between scientists (model developers) and resource managers (model users).

How should the quantitative data collected on fire-effects issues at the workshop be used in future analyses and implementation? First, one could use the results as is, selecting those items that are most important within each category (key question or response) and then working on the most practical of the important ones, or perhaps developing a combined, importance-practicality metric to use. Second, one could select specific results from each workgroup, using judgments from only certain members of each workgroup. The members, whose judgments are used in each case, could vary (i.e., the 3-4 centroid vectors for each matrix could be used), or the judgments from the most knowledgeable and rational members of each workgroup could be followed through each analysis. A third way to treat the results is to calculate global priorities for averaged workgroup rankings or for each workgroup member separately (i.e., propagating priorities from one level [key questions] down to the next [responses]). A final approach is to calculate true global priorities that take into account priorities of the four primary topics. It would be appropriate for a program manager or similar administrator to designate these high-level priorities.

We suggest limiting the number of workgroup-member judgments that are used to develop fire-effects research programs and priorities. Inconsistency in rankings across workgroup members in this effort made it difficult to obtain statistically significant results. The intent of the workshop was to clearly state the major fire-disturbance issues and to identify the priority tasks that lie ahead for scientists and resource managers. It is not necessary to rely on everyone that provided judgments; other members of the workgroups most certainly contributed in other ways (e.g., generating discussion or providing valuable insights). Those same insightful individuals may not necessarily be good at providing judgments or agreeing with others.

All of the recent "paradigms" that are currently part of the managerial lexicon of the Forest Service and other public agencies—ecosystem management, watershed analysis, landscape design, etc.—must be addressed with concepts of large spatial and temporal scales. The effects of fire disturbance on ecosystems are increasingly integrated into resource management plans as a "natural" process, or at least a strong consideration in fire management. The information compiled in this document represents a focused, detailed effort to identify key issues and approaches to assess the impacts of fire disturbance in both scientific and managerial contexts. This information can be used as a scientific platform describing where we are and what we know, which will allow us to better envision where it is we need to go. In so doing, it offers a template for ongoing and future fire-effects research and for facilitating communication between scientists and research managers. While the total list of issues and approaches stated here likely encompasses decades of additional research, we hope that the highest priority questions and issues will be the ones addressed in the scientific and resource management programs of the next few years.

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TABLES

Table 1--General classification of scales and examples of relevant fire characteristics, processes, and influences for each scale

Scale classification	Fire characteristics, processes, and influences
Micro	Energy flux, pyrolosis, personal attitude
Mechanical	Temperature, radiation, ignition, individual behavior
Sensory	Weather observation, fire behavior, suppression, human activity
Meso	Thunderstorm, fire danger, dispatch, supervision
Synoptic	Cold front, fire severity, mobilization, production
Strategic	Drought, fire season, fire planning, organizational budget
Macro	Climate, fire ecology, fire policy, government
Global	Climatic change, fire history, treaty

Source: Simard (1991). Reprinted with permission of the International Association of Wildland Fire.

Table 2--Links among fire effects, fuels, and climate key questions and their responses rated by importance and practicality

Key questions and responses	Importance	Practicality[a]
1. What, where, and when are the following factors important to fire disturbance?	0.38	—
Climate		
Fire		
Fuels		
Biota		
Physiography		
Humans		
2. What knowledge do we have about these links?	0.25	—
We must know fire severity, intensity, seasonality, and pattern to understand linkages and interactions	0.16	0.07
Large scale climatic events (synoptic) have a known frequency and fire effect	0.15	0.12
Paleoclimatic and current climate records are available and can be used with simulation models to extrapolate weather data	0.14	0.16
Preserve and analyze disturbance records on the landscape	0.13	0.08
A wide variety of fire history data exist and can be valuable	0.10	0.16
Fuels are much more variable (in time and space) than climate and their impact differs with fire severity	0.08	0.09
Intensity and severity of fire are very different; severity is related to fire effects, and intensity is related to behavior	0.08	0.11
Fire propagation processes are important to link with other ecosystem processes	0.08	0.09
Fire ignition has numerous sources and depends on fuel bed and moisture	0.07	0.12
3. At what scales are processes important?	0.17	—
Propagation of errors must be accounted for across scales	0.20	0.15
An ecological data structure spanning many scales is needed	0.16	0.08
A scale of analysis (e.g., landscape scale) must be defined to integrate coarse- and fine-scale processes	0.14	0.15
Multiple scales should be incorporated in simulation approaches	0.13	0.09
Explanatory coarse-scale models are needed to refine the predictive ability of other models	0.13	0.19
A cross-scale decision support tool is needed for managing wildland and	0.12	0.07

Key questions and responses	Importance	Practicality[a]
prescribed fire		
Fire characteristics must be intimately linked to weather and climatic processes	0.11	0.26
4. How are links related in a landscape context?	0.11	—
Landscapes need to be *engineered* to lie within acceptable limits of fire behavior and severity and still function as an ecosystem	0.28	0.14
A method is needed for evaluating the effectiveness of vegetation- and fuel-management strategies at the landscape level	0.21	0.15
A better understanding is needed of the influence of linked processes to landscape structure, composition, and function and vice versa	0.15	0.15
Need to predict fire regime from the other ecosystem processes	0.12	0.09
Landscape representations and analysis procedures are needed that are useful to both research and management	0.10	0.09
A better understanding is needed of how the adjacency of vegetation patches affects and is affected by heat from fires	0.08	0.25
A better understanding is needed of the dynamics of fire breaks spatially and temporally	0.07	0.14
5. What links have a high level of management importance?	0.08	—
The public needs to be encouraged to be actively involved in decisionmaking in ecosystem management	0.17	0.21
Scientists must provide a summary of current knowledge to management	0.17	0.26
A severity measurement (with units) is needed that integrates frequency, variability, intensity duration, season, and synergistic effects of fire	0.12	0.07
A system is needed to predict which processes enable fire events (risk) as they interact in both time and space	0.12	0.06
Fire regimes must be described quantitatively in terms of severity and intensity	0.11	0.05
Better predictions are needed of biotic responses as fire and climatic processes change	0.10	0.07
Technology is needed to manage large-scale events	0.08	0.08
A system is needed to predict emissions from fire	0.07	0.12
A better understanding is needed of the interaction of these processes on smoke production	0.06	0.10

[a] The workgroup elected not to compare key questions with respect to practicality. They also felt that the responses to key question 1 were too interrelated for comparisons to be made..

Table 3--Fire as a large-scale disturbance key questions and focused questions are rated according to importance

Key questions and focused questions	Importance[a]
1. What are the critical aspects of spatial and temporal dynamics of fire at large scales?	0.41
What characteristics of fire as a landscape/ecosystem disturbance are relevant to large-scale (spatial and temporal) modeling? What are the characteristics or forces that drive the behavior of a fire regime?	0.29
What is the feedback of fires on the greenhouse effect? What is the long-term interaction of fire, ecosystem structure, and climate? What role will potential climate change have on fire regimes How will fire frequency control vegetation composition with climate change?	0.25
What is the relative importance of the cumulative impact of small fires vs. the impact of rare large fires or extreme events?	0.15
How do we deal with heterogeneity in modeling large scale disturbance?	0.15
How important are areas that are missed by fires over several events as refugia for fire-sensitive species? What is the nature of areas that are refugia? What characteristics of these areas allowed them to be missed by fire events?	0.09
How do we deal with the stochastic nature of single events in fire regime?	0.08
2. What ecological role does fire play at larger scales?	0.28
What are the most important aspects of long-term changes in fire characteristics on vegetation? How is fire interrelated to other disturbance vectors? Does fire create stress in ecosystems or result from stress in ecosystems?	0.38
How does fire (regime and individual) impact ecosystem processes and dynamics?	0.38
What influence does past disturbance history have in shaping the current ecosystem structure (e.g., looking at two drainages that share the same disturbance regime)?	0.24
3. How can fire be managed at large scales?	0.17
How does landscape fragmentation affect large scale fire regimes?	0.27
What characteristic of a fire regime has the most importance (carries value) to the public?	0.23
How do we define appropriate fire regime for management objectives?	0.20
What are the relevant landscape and large-scale issues for political boundaries (management and policy differences)?	0.16
In a non-steady-state environment, how does one chose to manage for a particular landscape?	0.13
4. What are the critical characteristics of the fire-behavior environment?	0.15
Under what circumstances does crowning potential become the critical aspect of fire behavior for predicting effects?	0.51
In which environments can we assume that ignition sources are always available vs. scarce?	0.30
How important is fire size as a feature of the fire regime?	0.19

[a] The workgroup did not compare questions with respect to doability.

Table 4--Key questions and their responses for fire-effects modeling structures are rated according to importance and practicality.

Key questions and responses	Importance	Practicaility
1. How does one validate a model's structure with respect to error propagation?	0.22	
Need analyses of the sensitivity of internal components of the model to both data and to interactions with other models. We also need sensitivity analysis of transitions between model components at which there is spatial or temporal aggregation	0.27	0.12
Compare outputs of a model and model components to independent *data*	0.26	0.17
State the operational bounds for model inputs	0.25	0.34
Compare similar models to each other and with independent data	0.14	0.17
Compare model structures to structures from previously validated models. Disparate spatial and temporal scales of model application may, however, require different model structures.	0.08	0.21
2. What are the relevant spatial and temporal *scale issues* (including extent and resolution) related to modeling fire effects?	0.18	
Modeling needs to be spatially explicit and temporally dynamic. Model resolution needs to be finer than the extent desired for projection	0.22	0.11
Spatial and temporal variability in weather and climate, vegetation, fuels, and fire behavior is different at different scales	0.16	0.17
The appropriate temporal and spatial resolution and extent need to be determined for each modeling effort	0.15	0.18
Considerations of temporal aggregations are as important as consideration of spatial aggregations	0.13	0.11
The structure of fire-effects models may be different at different spatial and temporal scales	0.10	0.14
Most existing data on fire effects have been collected and analyzed at small spatial and temporal scales	0.10	0.12
The magnitude of the error needs to be quantified relative to the scale of implementation	0.08	0.10
Models need to be designed to minimize errors at the intended scale of implementation	0.06	0.07
3. What are the "ideal" fire-effects model outputs?	0.14	
Produce spatially explicit and immediate fire-effects outputs and generate necessary inputs for successional vegetation models.	0.33	0.30
Include physical and biological aspects so that the model has broad applicability, i.e. process based.	0.30	0.22
Relate fire behavior (flaming and smoldering combustion) to fire effects. Flaming combustion is typically associated with the fire front, and smoldering combustion occurs after the fire front passes or in ground (peat) fires.	0.28	0.25
Produce quantitative emission characteristics and time-dependent emissions.	0.10	0.24
4. How does one calibrate a fire-effects model?	0.12	
Individual components of the model should be calibrated separately.	0.24	0.23
To the extent possible, the model should be calibrated across the domain of the anticipated implementation.	0.22	0.12
Calibrate against theoretical standards, so that calibration is more than a sequence of adjustments to make the output "look right."	0.16	0.18
Resolution of the model should be consistent with the resolution of the data used for calibration.	0.16	0.15
Calibrate against a large amount of data.	0.13	0.10
Calibrate against another model.	0.09	0.21

5. How does scale affect the modeling approach?	0.09	
As the resolution of the model changes, the approach to modeling changes (e.g., from process based to statistical). Statistical properties of aggregates are often more easily estimated and modeled than components of these aggregates.	0.75	0.50
In the real world, the temporal and spatial scales of processes are variable. Thus aggregation error will occur when time steps and spatial resolution of different modeled processes are equalized.	0.25	0.50
6. What are the “ideal” fire-effects model components?	0.06	
7. What data are available for calibration, validation, and development of fire-effects models?	0.06	
8. What is the appropriate system structure (e.g., an integrated system of separate models or a unified model)?	0.05	
System modularity should reflect process modularity.	0.31	0.27
If model structure involves coupling independently developed models, internal consistency between analogous modules should be ensured and redundancy should be reduced.	0.29	0.23
Where possible, process-based models are preferred over statistical models.	0.26	0.18
The model should be structured as modular as possible.	0.14	0.31
9. How does one integrate climate into fire-effects modeling?	0.04	
10. What tools exist to generate data for the development of fire-effects models?	0.04	

Table 5--Management concerns, applications, and decision-support key questions and their responses are rated according to importance and practicality

Key questions and responses	Importance	Practicality
1. What are the most useful model structures and outputs, to support issues in planning, operations, monitoring and learning by resource managers, decision makers, policy makers and researchers?	0.43	0.15
Model to allow users to select fire regimes and show their probabilistic effects on the landscape	0.53	0.14
Data structures must be compatible with user capabilities	0.19	0.32
Develop hierarchical and selective modeling framework for fire regimes and fire effects (e.g., LOKI)	0.18	0.23
Communicate model limitations to users, and user needs to model builders	0.10	0.31
2. How do we improve communication between users and model builders (scientists), relative to the development life cycle?	0.28	0.44
Proactively seek opportunities to communicate	0.67	0.85
Build long-term relations	0.33	0.15
3. How can we rapidly and effectively transfer research information?	0.15	0.17
Improve documentation (user manuals, tutorials, online help, etc.) and model support (technical support, programming, scientific documentation, software distribution and support via Internet, etc.), apply product life cycles	0.39	0.13
Standardize and provide desired user interfaces (GUI)	0.27	0.31
Explore alternate means for accomplishing data management (e,g., contracting) and technology transfer	0.13	0.33
Establish and support a development group	0.13	0.14
Apply free market principles (product development, support and distribution)	0.09	0.10
4. How can we incorporate *social* and *political* issues into models and decision-support systems?	0.07	0.06
Incorporate sociological research when developing decision-support systems	0.66	0.53
Modelers and managers must be aware of emerging issues and anticipate future concerns	0.34	0.47
5. How can relevant interdisciplinary resource management issues be incorporated into models?	0.06	0.18
Improve communication between modelers and users	0.61	0.40
Involve a cross-section of managers and policymakers in model development	0.29	0.38
Assign responsibility, develop measurement criteria, monitor accomplishment and provide accountability for both research and management	0.10	0.22

Table 6--Probability values generated by the Wilcoxon signed-ranks test for differences across means of the importance-rating scores for the key questions related to links among fire effects, fuels, and climate

Key question[a]	Management importance	Knowledge	Factors	Landscape	Scales
Management importance	1.000				
Knowledge	.028	1.000			
Factors	.028	.068	1.000		
Landscape	.249	.028	.028	1.000	
Scales	.028	.173	.028	.225	1.000

[a]See table 2 for a complete description of each key question.

Table 7--Probability values for agreement on importance rankings (Friedman) and differences in mean rating scores (Kruskal-Wallis) for key questions for the workgroup dealing with links among fire effects, fuels, and climate

Key question[a]	Friedman test probability	Kruskal-Wallis probability
Factors	—	—
Knowledge	0.143	0.115
Scales	.833	.868
Landscape	.020	.007
Management importance	.179	.048

[a] See table 2 for a complete description of each key question.

Table 8--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to"What ecological role does fire play at larger scales?"(key question 2) for links among fire effects, fuels, and climate

	Responses to key question 2[a]								
Responses to key question 2[a]	Synoptic	Records	Preserve	Fuels	Intense, severe	Know fire	Propa-gation	Ignition	Fire data
Synoptic	1.000								
Records	.917	1.000							
Preserve	.463	.686	1.000						
Fuels	.345	.463	.345	1.000					
Intense, severe	.463	.345	.345	.753	1.000				
Know fire	.917	.500	.345	.249	.068	1.000			
Propagation	.116	.046	.116	.686	.500	.043	1.000		
Ignition	.046	.046	.116	.463	.686	.043	.500	1.000	
Fire data	.463	.463	.249	.917	.686	.043	.465	.500	1.000

[a] See table 2 for a complete description of responses to key question 2.

Table 9--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to "What are the critical characteristics of the fire-behavior environment?" (key question 4) for links among fire effects, fuels, and climate

	Responses to key question 4						
Responses to key question 4	Fire breaks	Linked processes	Adjacency	Fuel mgmt.	Engineer	Predict regime	Procedures
Fire breaks	1.000						
Linked processes	.028	1.000					
Adjacency	.600	.173	1.000				
Fuel mgmt.	.075	.345	.043	1.000			
Engineer	.046	.173	.068	.345	1.000		
Predict regime	.173	.463	.345	.138	.043	1.000	
Procedures	.345	.345	.500	.138	.043	.893	1.000

Table 10--A Wilcoxon signed-ranks test generates a matrix of probability values for differences across means for the importance-rating scores of responses to "What links are important to management" (key question #5) for links among fire effects, fuels, and climate.

	Responses to key question 5[a]								
Responses to key question 5[a]	Enabling	Techno-logy	Biotic response	Severity measure	Fire regime	Know mgmt.	Emissions	Smoke	Public
Enabling	1.000								
Technology	0.116	1.000							
Biotic response	0.500	0.116	1.000						
Severity measure	.686	.138	.715	1.000					
Fire regime	.345	.116	1.000	.893	1.000				
Know mgmt.	.753	.043	.345	.600	.345	1.000			
Emissions	.173	.600	.463	.116	.173	.028	1.000		
Smoke	.173	.463	.249	.173	.116	.028	.285	1.000	
Public	.753	.043	.249	.500	.249	.249	.028	.028	1.000

[a] See table 2 for a complete description of responses to key question 5.

Table 11--Probability values for agreement on importance rankings (Friedman) and differences in mean rating scores (Kruskal-Wallis) of responses to key questions with respect to practicality rankings for the workgroup dealing with links among fire effects, fuels, and climate

Key question[a]	Friedman test probability	Kruskal-Wallis probability
Factors	—	—
Knowledge	0.356	0 .531
Scales	.083	.040
Landscape	.280	.233
Management importance	.001	.000

[a] See table 2 for a complete description of responses to key questions.

Table 12--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to"At what scales are processes important?"(key question 3) for links among fire effects, fuels, and climate

Responses to key question 3[a]	Responses to key question 3[a]						
	Climate	Decision support tool	Multiple scales	Ecological data	Explanatory	Errors	Landscape scale
Climate	1.000						
Decision support tool	.144	1.000					
Multiple scales	.068	1.000	1.000				
Ecological data	.068	.715	.715	1.000			
Explanatory	.273	.273	.068	.109	1.000		
Errors	.465	.273	.144	.285	.655	1.000	
Landscape scale	.068	.273	.068	.068	.273	1.000	1.000

[a] See table 2 for a complete description of responses to key question 3.

Table 13--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to"How are links related in a landscape context?"(key question 4) for links among fire effects, fuels, and climate

Responses to key question 4[a]	Responses to key question 4[a]						
	Fire breaks	Linked processes	Adjacency	Fuel mgmt.	Engineer	Predict regime	Procedures
Fire breaks	1.000						
Linked processes	.686	1.000					
Adjacency	.043	.463	1.000				
Fuel mgmt.	.893	.686	.116	1.000			
Engineer	.893	.893	.144	.686	1.000		
Predict regime	.138	.249	.043	.116	.138	1.000	
Procedures	.345	.345	.116	.500	.345	.463	1.000

[a] See table 2 for a complete description of responses to key question 4.

Table 14--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to"What links are important to management?"(key question 5) for links among fire effects, fuels, and climate

	Enabling	Technolog y	Biotic response	Severity measure	Fire regime	Know mgmt.	Emis-sions	Smoke	Public
Enabling	1.000								
Technology	.686	1.000							
Biotic response	.715	.080	1.000						
Severity measure	.753	.753	.345	1.000					
Fire regime	.917	.345	.249	.593	1.000				
Know mgmt	.028	.028	.028	.028	.028	1.000			
Emissions	.345	.116	.075	.173	.116	.028	1.000		
Smoke	.463	.600	.116	.345	.225	.028	.109	1.000	
Public	.028	.046	.028	.028	.028	.225	.075	.075	1.000

[a]See table 2 for a complete description of responses to key question 5.

Table 15--A Probability values generated by the Wilcoxon signed-ranks test for differences across means of the importance-rating scores for the key questions related to fire as a large-scale disturbance

Key questions[a]	Key questions[a]			
	Ecological	Managed	Dynamics	Fire Behavior
Ecological	1.000			
Managed	.465	1.000		
Dynamics	.273	.068	1.000	
Fire Behavior	.138	.500	.068	1.000

[a]See table 3 for a complete description of key questions.

Table 16--Probability values for agreement on importance rankings (Friedman) and differences in mean rating scores (Kruskal-Wallis) for key questions for the workgroup dealing with fire as a large-scale disturbance.

Key question[a]	Friedman test probability	Kruskal-Wallis probability
Dynamics	0.074	0.041
Ecological	.861	.537
Managed	.401	.384
Fire behavior	.350	.126

[a]See table 3 for a complete description of key questions.

Table 17-- Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to"What are the critical aspects of spatial and temporal dynamics of fire at large scales?"(key question 1) for fire as a large-scale disturbance.

Responses to key question 1[a]	Responses to key question 1[a]					
	Modeling	Stochastic	Refugia	Climate	Impact	Heterogeneity
Modeling	1.000					
Stochastic	.043	1.000				
Refugia	.068	.465	1.000			
Climate	.893	.080	.080	1.000		
Impact	.144	.043	.144	.080	1.000	
Heterogeneity	.144	.068	.225	.138	.686	1.000

[a]See table 3 for a complete description of responses to key question 1.

Table 18--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to "How can fire be managed at large scalse?" (key question 3) for fire as a large-scale disturbance

Responses to key question 3[a]	Responses to key question 3[a]				
	Landscape	Management objectives	Public	Political	Fragmentation
Landscape	1.000				
Management objectives	.465	1.000			
Public	.225	.893	1.000		
Political	.345	.686	.500	1.000	
Fragmentation	.080	.686	.893	.043	1.000

[a]See table 3 for a complete description of responses to key question 3.

Table 19--Probability values for agreement on importance rankings (Friedman) and differences in mean rating scores (Kruskal-Wallis) for the most important focused questions within each key question for the workgroup dealing with large-scale disturbance

Focused question[a]	Friedman test probability	Kruskal-Wallis probability
Dynamics 1	0.787	0 .690
Dynamics 2	.779	.885
Ecological 1	.406	.572
Ecological 2	.919	.883
Managed 1	.739	.153
Managed 2	.067	.018
Managed 3	.196	.095
Fire behavior 1	.247	.133
Fire behavior 2	.770	.572

[a]See table 3 for a complete description of key questions and focused questions.

Table 20--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to "What characteristic of a fire regime has the most importance to the public?" (focused question 2) under "How can fire be managed at large scales?" (key question 3) for fire as a large-scale disturbance

	Response to focused question 2[a]				
Responses to focused question 2[a]	Aesthetics	Safety	Perceptions	Acceptable	Smoke
Aesthetics	1.000				
Safety	.068	1.000			
Perceptions	.144	.225	1.000		
Acceptable	.043	.715	.465	1.000	
Smoke	.068	.068	.893	.138	1.000

[a]See table 3 for a complete description of key questions and focused questions.

Table 21--Probability values generated by the Wilcoxon signed-ranks test for differences across means of the importance-rating scores for the key questions related to fire-effects modeling structures

	Key questions[a]									
Key questions[a]	Scale issues	Model comps.	Calibra-tion	Validation	Climate	Scale effects	Structure	Model outputs	Data available	Data tools
Scale issues	1.000									
Model comps.	.043	1.000								
Calibration	.141	.173	1.000							
Validation	.249	.046	.043	1.000						
Climate	.028	.344	.046	.028	1.000					
Scale effects	.028	.345	.500	.028	.116	1.000				
Structure	.027	.786	.027	.028	.600	.207	1.000			
Model outputs	.917	.043	.248	.345	.116	.279	.115	1.000		
Data available	.046	.833	.248	.028	.916	.345	.528	.144	1.000	
Data tools	.027	.293	.027	.028	.598	.046	.136	.116	.414	1.000

[a]See table 4 for a complete description of key questions.

Table 22--Probability values for agreement on importance rankings (Friedman) and differences in mean rating scores (Kruskal-Wallis) for the six most important key questions for the workgroup dealing with fire-effects modeling structures

Key questions[a]	Friedman test probability	Kruskal-Wallis probability
Validation	0.008	0.004
Scale issues	.025	.014
Model outputs	.130	.085
Calibration	.419	.083
Scale effects	.041	.004
Structure	.246	.202

[a]See table 4 for a complete description of key questions.

Table 23--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to "How does one validate a model's structure with respect to error propagation?" (key question 1) for fire-effects modeling structures

	Responses to key question 1[a]				
Responses to key question 1[a]	Compare to data	Compare to models	Compare structure	Sensitivity	Bounds
Compare to data	1.000				
Compare to models	.080	1.000			
Compare structure	.028	.043	1.000		
Sensitivity	.686	.046	.028	1.000	
Bounds	.500	.249	.028	.893	1.000

[a]See table 4 for a complete description of responses to key question 1.

Table 24--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to "What are the relevant spatial and temporal scale issues (including extent and resolution) related to modeling fire effects?" (key question 2) for fire-effects modeling structures

	Responses to key question 2[a]							
Responses to key question 2[a]	Resolution & extent	Minimize error	Quantify error	Variability	Small scales	Fine resolution	Temporal aggregation	Structure
Resolution & extent	1.000							
Minimize error	.046	1.000						
Quantify error	.249	.686	1.000					
Variability	.917	.028	.345	1.000				
Small scales	.463	.046	.600	.138	1.000			
Fine resolution	.345	.028	.116	.249	.028	1.000		
Temporal aggregation	.753	.046	.345	.893	.345	.075	1.000	
Structure	.075	.249	.753	.249	.917	.046	.500	1.000

[a]See table 4 for a complete description of responses to key question 2.

Table 25--Probability values for agreement on practality rankings (Friedman) and differences in mean rating scores (Kruskal-Wallis) for the six most important key questions for the workgroup dealing with fire-effects modeling structures

Key question[a]	Friedman test probability	Kruskal-Wallis probability
Validation	0.212	0 .064
Scale issues	.010	.008
Model outputs	.950	.928
Calibration	.045	.061
Scale effects	1.000	1.000
Structure	.849	.407

[a]See table 4 for a complete description of key questions.

Table 26--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the practality-rating scores of responses to "What are the relevant spatial and temporal scale issues (including extent and resolution) related to modeling fire effects?" (key question 2) for fire-effects modeling structures

	Responses to key question 2[a]							
Responses to key question 2[a]	Resolution & extent	Minimize error	Quantify error	Variability	Small scales	Fine resolution	Temporal aggregation	Structure
Resolution & extent	1.000							
Minimize error	.028	1.000						
Quantify error	.028	.068	1.000					
Variability	.600	.028	.028	1.000				
Small scales	.116	.075	.917	.345	1.000			
Fine resolution	.046	.138	.345	.173	.917	1.000		
Temporal aggregation	.173	.075	.400	.043	.600	.917	1.000	
Structure	.116	.028	.138	.463	.753	.686	.345	1.000

[a]See table 4 for a complete description of responses to key question 2.

Table 27--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the practality-rating scores of responses to "How does one calibrate a fire-effects model?" (key question 4) for fire-effects modeling structures

	Responses to key question 4[a]					
Responses to key question 4[a]	Against data	Against model	Against theory	Consistency	Components	Domain
Against data	1.000					
Against model	.043	1.000				
Against theory	.138	.465	1.000			
Consistency	.463	.116	.116	1.000		
Components	.116	.917	.463	.116	1.000	
Domain	.753	.116	.043	.068	.028	1.000

[a]See table 4 for a complete description of responses to key question 4.

Table 28--Probability values generated by the Wilcoxon signed-ranks test for differences across means of the importance-rating scores for the key questions related to management concerns, applications, and decision support

	Key questions[a]				
Key questions[a]	Relevance	Communication	Info transfer	Model structures	Sociopolitical
Relevance	1.000				
Communication	.028	1.000			
Info transfer	.028	.046	1.000		
Model structures	.028	.173	.028	1.000	
Sociopolitical	.753	.028	.075	.028	1.000

[a]See table 5 for a complete description of key questions.

Table 29--Probability values for agreement on importance rankings (Friedman) and differences in mean rating scores (Kruskal-Wallis) for key questions for the workgroup dealing with management concerns, applications, and decision support

Key question[a]	Friedman Test probability	Kruskal-Wallis probability
Model structures	.035	.007
Communication	.221	.041
Information transfer	.119	.024
Sociopolitical	.414	.068
Relevant	.006	.001

[a]See table 5 for a complete description of key questions.

Table 30--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to “What are the most useful model structures and outputs to support issues in planning, operations, monitoring, and learning by resource managers, decision makers, policy makers, and reserachers?” (key question 1) for management concerns, applications, and decision support

	Responses to key question 1[a]			
Responses to key question 1[a]	Communicate	Fire regimes	Data structures	Framework
Communicate	1.000			
Fire regimes	.028	1.000		
Data structures	.249	.046	1.000	
Framework	.463	.075	.753	1.000

[a]See table 5 for a complete description of responses to key question 1.

Table 31--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to “How can we reapidly and effectively transfer research information?” (key question 3) for management concerns, applications, and decision support

	Responses to key question 3[a]				
Responses to key question 3[a]	Explore	Improve	GUI	Support	Free market
Explore	1.000				
Improve	.075	1.000			
GUI	.249	.116	1.000		
Support	.917	.075	.075	1.000	
Free market	.345	.116	.249	.753	1.000

[a]See table 5 for a complete description of responses to key question 3.

Table 32-- Probability values generated by a Wilcoxon signed-ranks test for differences across means for the importance-rating scores of responses to "How can relevant interdisciplinary resource management issues be incorporated into models?" (key question 5) for management concerns, applications, and decision support

	Responses to key question 5[a]		
Responses to key question 5[a]	Involve	Assign	Improve
Involve	1.000		
Assign	.028	1.000	
Improve	.046	.028	1.000

[a]See table 5 for a complete description of responses to key question 5.

Table 33--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the practicality-rating scores for the key questions for management concerns, applications, and decision support

	Key questions[a]				
Key questions[a]	Relevance	Communication	Info transfer	Model structures	Sociopolitical
Relevance	1.000				
Communication	.043	1.000			
Info transfer	.686	.144	1.000		
Model structures	.893	.225	.893	1.000	
Sociopolitical	.138	.043	.068	.225	1.000

[a]See table 5 for a complete description of key questions.

Table 34--Probability values for agreement on importance rankings (Friedman) and differences in mean rating scores (Kruskal-Wallis) for practality of key questions for the workgroup dealing with management concerns, applications, and decision support

Key question[a]	Friedman Test probability	Kruskal-Wallis probability
Model structures	0.602	0 .373
Communication	.025	.007
Information transfer	.256	.060
Sociopolitical	.655	.745
Relevant	.549	.468

[a]See table 5 for a complete description of key questions.

Table 35--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the practicality-rating scores for responses to "How do we imporve communication between users and model builders (scientists) relative to the development life cycle?" (key question 2) for management concerns, applications, and decision support

	Responses to key question 2[a]	
Responses to key question 2[a]	Proactive	Build
Proactive	1.000	
Build	.039	1.000

[a]See table 5 for a complete description of responses to key question 2.

Table 36--Probability values generated by a Wilcoxon signed-ranks test for differences across means for the practicality-rating scores for responses to "How can we rapidly and effectively transfer research information?" (key question 3) for management concerns, applications, and decision support

	Responses to key question 3[a]				
Responses to key question 3[a]	Explore	Improve	User interface	Support	Free market
Explore	1.000				
Improve	.345	1.000			
User interface	.500	.345	1.000		
Support	.225	.893	.345	1.000	
Free market	.068	.893	.080	.686	1.000

[a]See table 5 for a complete description of responses to key question 3.

Figure 5—The hierarchical structure of the strawman document illustrates a portion of one primary topic, including key questions, scope, and example responses for that key question. Workgoup responses to key questions identify important issues and their practicality, which then enable us to recommend and prioritize research projects. All key questions were assessed in a similar fashion.