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Assessing the Effects of Fire Disturbance on Ecosystems: A Scientific Agenda for Research and Management

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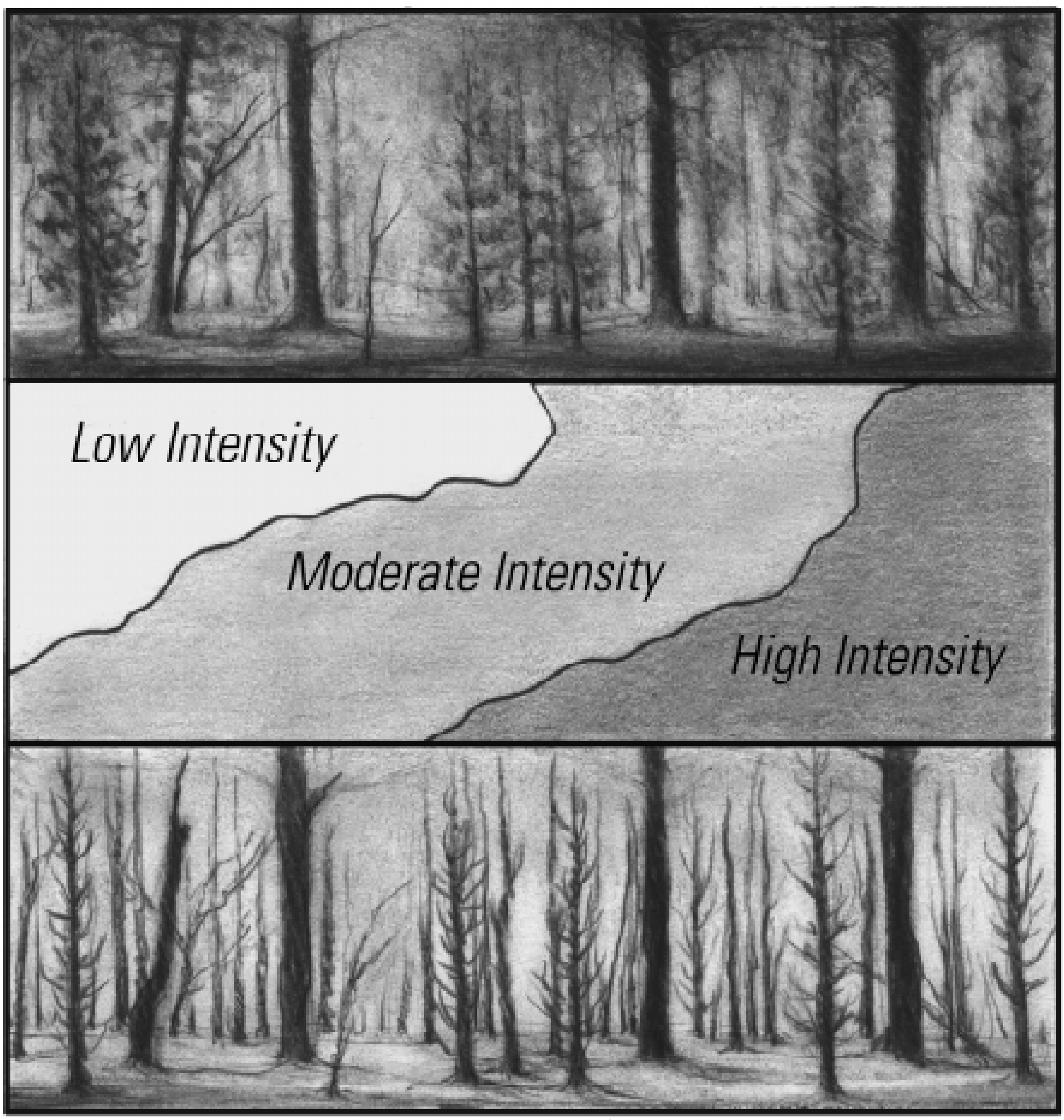

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Abstract

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A team of fire scientists and resource managers convened 17-19 April 1996 in Seattle, Washington, 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 included a series of numerically ranked scientific and managerial questions and responses focusing on (1) links 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 of fire effects and the ability to extrapolate fire-effects knowledge to large spatial scales are 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 expedient 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 to use 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.

Keywords: Analytic hierarchy process, ecological disturbance, fire effects, large-scale fire, modeling.

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. Most fire-effects data have been collected at small spatial scales, but 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 logically. 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) links 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 sufficient financial and human resources will be available to collect the information needed to 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 by using the analytic hierarchy process, so that 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 temporally infrequent, they have large-scale spatial impacts: 1 percent of all wildland fires in the Western United States may be responsible for as much as 98 percent 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 (fig. 1). Fire is the most important periodic natural disturbance in most forest, shrubland, and grassland ecosystems of western North America (Rogers 1996).

Although 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 into sharp focus in 1988 during and after the large fires in the Yellowstone National Park region. Although paleoecological evidence indicates that fires of this magnitude (about 5000 square kilometers total land area) had occurred previously in the region (Romme and Despain 1989), agency resource managers, administrators, and the general public seemed 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 for 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 square kilometers

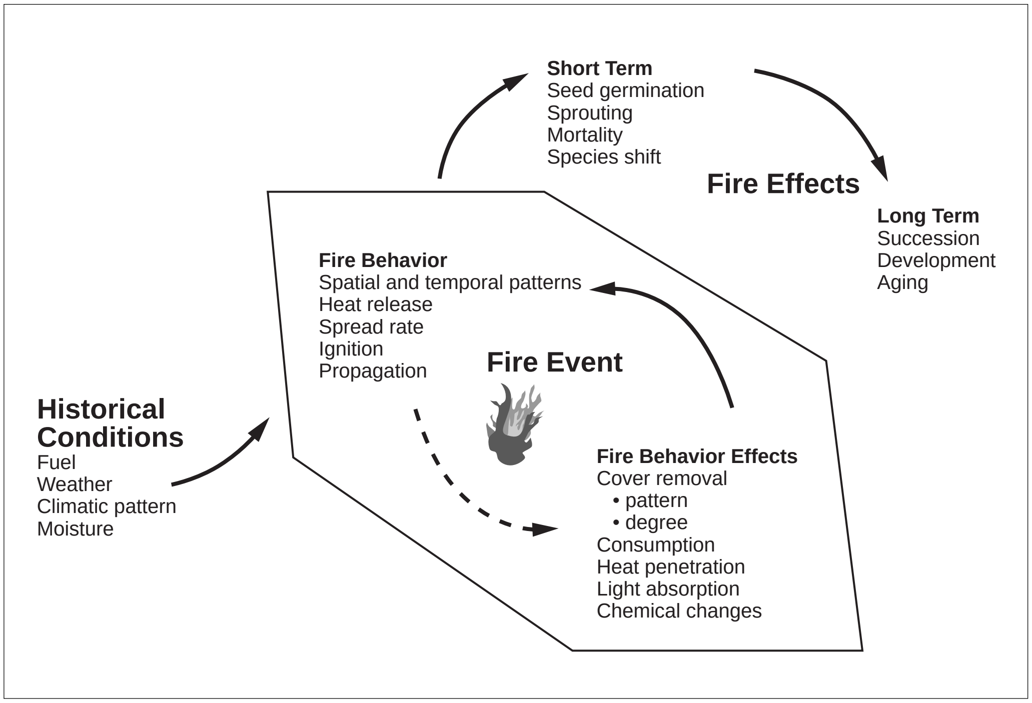

Figure 1—Large-scale fires have many effects and complex interactions. Figure from Paysen and others 1998.

(McKenzie and others 1996a). Extrapolating 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.

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 incorporating fire stochastically; and (3) landscape-level models of disturbance. These models operate on different spatial and temporal scales, although output from the first two types of models often is aggregated to larger scales.

Extrapolating ecological effects of fire across spatial scales can result in many sources of error, including (1) directly extrapolating fire behavior models 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

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.

of interest. Regardless of which approach is used, extreme fire events pose a major problem for modelers owing 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 rain forest, alpine meadows, east-side pine forest, and semiarid shrub-steppe.

The diversity of environmental conditions and ecosystems in the Pacific Northwest produces several fire regimes, which can be defined by characteristics of the disturbance (fig. 2), characteristics of the vegetation, or fire severity (fig. 3) (Agee 1993). With respect to fire-severity classification, high-severity fire regimes have 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 and 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 in grassland and shrubland ecosystems tend to be in low- and moderate-fire severity regimes in frequency but with rapidly moving, high-intensity fires.

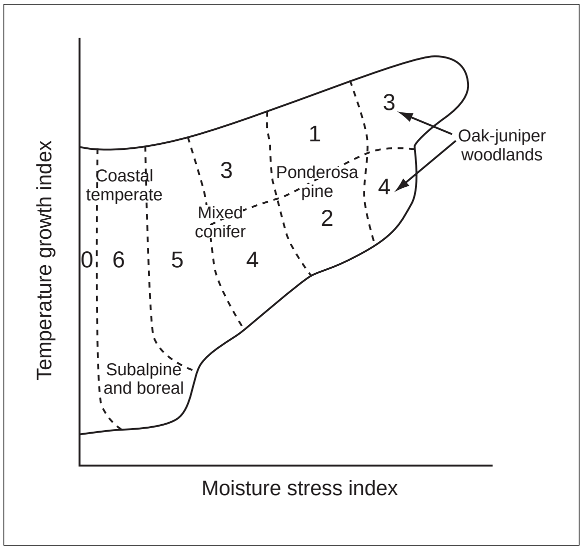

Figure 2—Fire regimes in Pacific Northwest vegetation types can be defined by physical characteristics of the disturbance (0=little fire influence, 1=infrequent light surface fire [>25 yr], 2= frequent light surface fire [1-25 yr], 3=infrequent severe surface fire [> 25 yr], 4= short return interval 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; granted with permission from “Fire Ecology of Pacific Northwest Forests,” Agee, ©,Island Press, Aug.13, 1998. Published by Island Press, Washington, DC, and Covelo, CA).

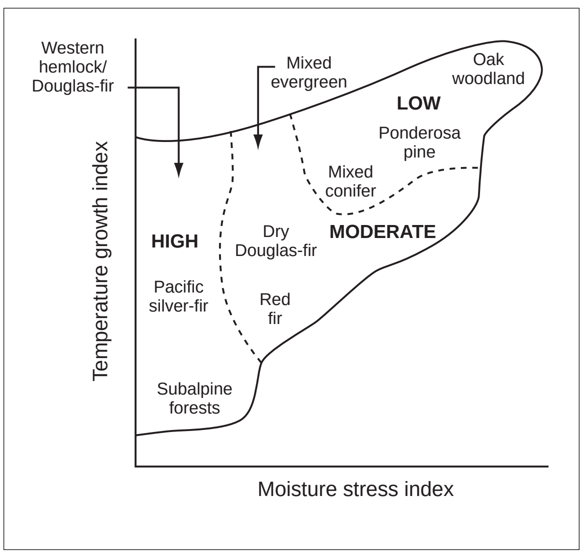

Figure 3—Fire regimes in the Pacific Northwest can be defined by fire severity. Stands in low-severity fire regimes have <20 percent of basal area removed by fire, and stands in high-severity fire regimes have >70 percent basal area removed. From Agee (1993), reproduced by permission, Island Press.

Recent large fires (over 800 square kilometers of land area in 1994) in forest ecosystems on the east side of the Cascade Range have posed a number of ecological, managerial, and political problems. 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 Range and in the Olympic Mountains have burned more than 10 000 kilometers 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 public agencies to manage. Perhaps appropriate vegetation and fuels management can mitigate fire severity or restore fire regimes that existed during the past few centuries, but 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 to improve our understanding and managerial approaches to fire disturbance in ecosystems. We need to establish priorities now 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 for a fire-disturbance workshop at the University of Washington to discuss these issues. The objectives of the workshop were to (1) identify the current state of knowledge for 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 decisionmaking for fire disturbance in resource management. Although the focus was on the Pacific Northwest, issues of broader national and global concern also were addressed. A structured workshop process was used to conduct discussions, compile information, and elicit knowledge from participants. Our previous experience with technical workshops (Peterson and others 1992, 1993; Schmoldt and Peterson 1991) demonstrated that predetermined structure is important for achieving useful workshop results.

We wanted to achieve a number of objectives, both strategic and tactical, during and after the meeting. Strategic objectives for this workshop are listed above and in the straw man document (a suggested framework or template, subject to revision, which is used as a basis for discussion and analysis) (fig. 4). These objectives deal with the overall accomplishments proposed for the workshop; i.e., describing, assessing, prioritizing, and recommending large-scale fire-disturbance research and managerial needs. A detailed tactical plan for achieving the strategic objectives also was 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 on large-scale fire disturbances that could be used to guide future research and resource management efforts by the U.S. Department of Agriculture, Forest Service and cooperators, particularly in the Pacific Northwest Region.
- Efficiency—To collect these judgments within a short time: 2 days.
- Product—To collect this expertise in a detailed and structured manner so that results could be formulated into a publishable report (this paper) reflecting the current state of knowledge about large-scale fire disturbance and future scientific and managerial needs.

Figure 4—The straw man 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.

Links 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. Institutions need to cooperate 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 relation of this variability to impacts on ecosystems must be examined.
- The relative impact of fuels and weather will differ 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 for vegetation composition and structure. The relative impact differs 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 previously having no fires can alter landscape patterns and disrupt previous ecosystem structure and functional relations.

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 and 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, though, that weather and topography often interact at 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 differ by latitude, longitude, and altitude (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 after fire.

Fire effects modeling structures

What existing models (or components) could be adapted or modified for proposed work by the Forest Service and cooperators? 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 were 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 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 the steady-state or the 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 climatic 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 policymakers?

- Incorporating a probabilistic approach will provide a more realistic range of output rather than a single "answer." Note, though, that although probabilities can be tracked, either rigorously or ad hoc, generating multiple scenarios for particular inputs (as mentioned below) will be the most useful for managers. By using the most likely array 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 array 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.

The organization and process of the workshop were designed with these tactical objectives of content, efficiency, and product in mind. The decisionmaking and group discussion protocols that were developed included three main parts: (1) assign attendees into discrete workgroups, which were the foci for workshop discussions; (2) create a conceptual structure for organizing workgroup discussion, a context for the discussion content; and (3) develop a seven-step process for workgroup conduct to streamline identifying, assessing, prioritizing, and recommending research and managerial needs. Workshop discussion centered around four broad content areas, or primary topics: (1) links 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 of them, we opted for small working groups rather than one large session. Each workgroup consisted of four to seven 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. For each key question, they were asked to provide corresponding responses. Workgroups also were asked to prioritize their list of key questions and, separately, their lists of responses within each question. Priorities were assigned for both importance and feasibility (or practicality). The analytic hierarchy process (Saaty 1980, 1990) was used within this group setting to arrive at priorities. This conceptual structure is shown in figure 5. After 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 were 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 on details of the workshop's conceptual structure and process. Readers are referred to Schmoldt and Peterson (1997) for specific methodology.

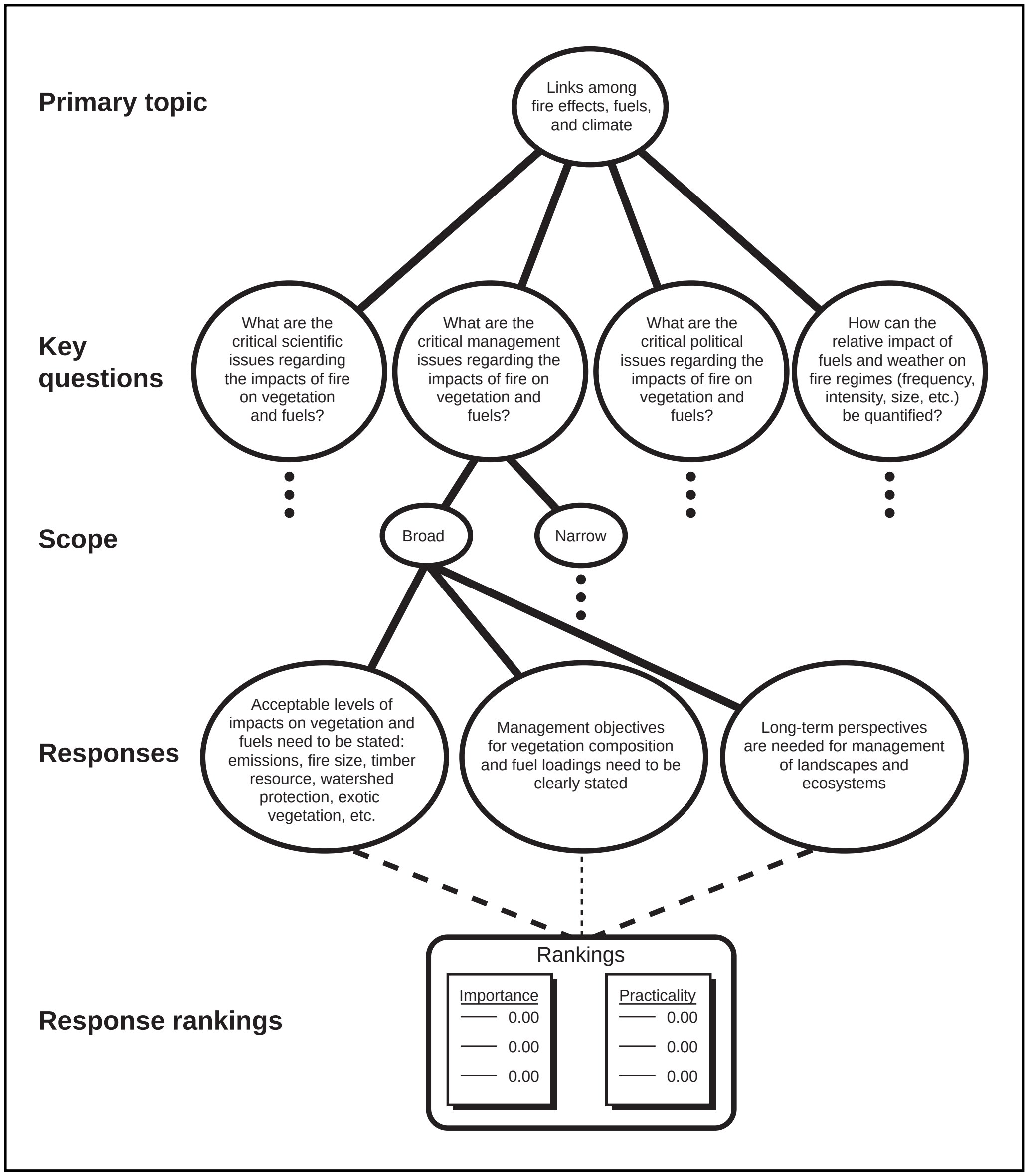

Figure 5—An illustration of the hierarchical structure of the straw man document for a portion of one primary topic, including key questions, scope, and example responses for that key question. Workgroup responses to key questions identify important issues and their practicality, which then enable us to recommend and prioritize research projects. All key questions were assessed similarly.

Workgroups met for discussions on one day, plus two hours on another day. 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.

The following four sections describe issues addressed and results produced in workgroup discussions. Despite the overall conceptual structure provided for the workgroups, each topic differs in difficulty, current knowledge, and available information. These differences dictated adjustments to the discussion process to fit specific needs. Consequently, the report of each workgroup differs in style, level of detail, and extent.

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Links Among Fire Effects, Fuels, and Climate[1]

Key Questions and Responses

This workgroup developed five questions important to understanding the links among fire, fuels, and climate. These key questions are presented below in descending order of importance. For each question, the group generated some general statements about the subject matter of the question to establish a context for response discussions. The group then produced a set of responses to each question to define current research and management needs. Each response was rated by the group on a final scale of 0 to 1 (using the methodology presented in Schmoldt and Peterson 1997) as to its (1) importance to management and research and (2) its “practicality” as defined by the probability of successfully researching the problem and implementing a solution. In addition, each key question posed by the group received a rating of importance. Practicality 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 practicality ratings for the key questions and responses appears in table 2.

[1] Workgroup members who developed this section: James Agee, Larry Bradshaw, Sheri Gutsell, Emily Heyerdahl (Recorder), Robert Keane (Leader), Ken Lertzman, and Kevin McKelvey.

Many factors other than fuels and climate affect fire. The workgroup limited its discussion to fuels and climate, however, because it believed they are the most important; moreover, to include in this discussion all processes affecting fire and its subsequent effects would be unmanageable. The first key question therefore 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.

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

Key questions and responses[a]	Importance	Practicality[b]
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 links 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 climatic 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

Table 2—Links among fire effects, fuels, and climate key questions and their responses rated by importance and practicality (continued)

Key questions and responses[a]	Importance	Practicality[b]
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 prescribed fire	0.12	0.07
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

Table 2—Links among fire effects, fuels, and climate key questions and their responses rated by importance and practicality (continued)

Key questions and responses[a]	Importance	Practicality[b]
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] Underlined words are used as shorthand notation in analyses in tables 6-14, p. 66-70.

[b] The workgroup did not 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.

Question 1: What, where, and when are fuels and climate 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 individually. 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 among these factors, the group decided not to generate importance or practicality ratings for the responses to this first question. Instead, these factors were used as background for all other questions.

The first part of the question "What are the important factors?" was discussed in detail, and it was decided that the following list would generally describe those 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, 1990b; Johnson 1992; Johnson and Wowchuk 1993; 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, 1992; Johnson and Larsen 1991; Johnson and Van Wagner 1985; Masters 1990).
- Fuels: Both dead and live organic matter contribute to the combustion process. Fuels include both living and dead vegetation and are highly influenced by vegetation structure. Fuels 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 comprise the biota. The type of vegetation affects live and dead fuel characteristics and the nature of fire behavior. Fire effects range 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, 1992; Prentice and others 1993; Wright and Bailey 1982).
- Physiography: Slope, aspect, landform, slope shape, slope position, and elevation define physiography. 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 influence fire and ecosystem dynamics on the landscape (Pyne 1982, 1984).

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

- Extreme fire events currently burn the most area. Only about 1 percent of fires burn over 98 percent of the involved 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 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 influencing fire dynamics in nonextreme years.
- Fire behavior in the nonextreme 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 needs statements generated by the workgroup:

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

After careful deliberation, the workgroup decided on 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 additional human-oriented factors influence these links? 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 links? Did native peoples change the pattern of fire or complement existing patterns?

Question 2: What do we know about these links?

The workgroup assessed existing knowledge about processes affecting coarse-scale fire dynamics to identify possible research areas. This knowledge base includes literature, models, databases, spatial data layers, and expert systems. Responses were stratified by individual fire-related processes, recognizing that interactions are important. Some broad statements were developed to provide a context for an 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 Larsen 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, 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 as a result of 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 typically are the most severe and intense.

Current knowledge of climate and climatic data—

Long-term climatic records—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), and sunspot records (Allison and others 1986, Arens 1990, Gajewski 1987, Hopkins and others 1993, Singh and others 1981, Swain 1973, Swetnam and Baisan 1996). 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 Center and Canadian Atmospheric Environment Service (50 to 100 years B.P.), U.S. Natural Resources Conservation Service (SNOTEL) (1980 to present), and U.S. Department of Agriculture (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 1997) 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 (Schlesinger and Mitchell 1987) and GISS (Hansen and others 1988), with mechanistic regional-scale models. 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 general circulation model 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 affecting 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). The most important fuel variables affecting ecosystem dynamics are probably loading, coarse woody debris (size, length, rot), duff depth and distribution, snag density, moisture content, and particle distribution.

Links between fire and fuels are different than links 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 controlled mainly by saturation during rainy periods or in winter. Fire, on the other hand, is strongly affected by quantities of fine fuels and their moisture contents, which differ day-to-day with atmospheric humidity. Under low to moderate fire weather conditions, large, ecologically important elements often will be only partially consumed by fire. In extreme drought conditions, however, these large logs burn over long 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 soil properties (Albini and others 1996, Wells and others 1979).

Available temporal fuels data—Few studies of temporal variation of fuels in the United States have permanent plots. Some that do include the Sierra Nevada, Yosemite National Park (7 years and ongoing), Yellowstone National Park (Renkin and Despain 1992), western Cascades (Spies and others 1988), western Montana, (5 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:

- Fuel descriptions, photo series (Fischer 1981)
- Fuel databases (Brown and See 1981, Jeske and Bevins 1976)
- Sierra Nevada Ecosystem Project (SNEP 1996)
- Montana and 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 (Hardy and others, in press; Loveland and others 1991)
- 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, 1996c) and also see Shugart and West (1980).

Fire

Fire is 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 links and interactions in fire dynamics. The most important fire-behavior characteristics are listed below with their unit of measure where appropriate. The variability of fire intervals may have a major effect on the character of the vegetation.

- Fuel consumption (kilograms per square meter)
- Rate of spread, intensity (meters per second, kilowatts per meter)
- Duration (smoldering vs. direct combustion)
- Size and pattern (hectares)
- Soil heat pulse (degrees Celsius)
- Frequency (per year) and its variability
- Surface versus crown fire
- Smoke and emissions (kilograms per hectare)
- Propagation processes
- Spot-fire mechanisms
- Ignition dynamics (sources, fuel bed, moisture)

Fire models—Several spatial and nonspatial fire models are available. Among them are BEHAVE (Andrews 1986), FARSITE (Finney 1994, 1995; Finney and Ryan 1995), Canadian Fire Behavior Prediction System (van Wagner 1987), and cellular automata models (Clark and others 1994). All, however, have some limitations, including restricted mostly to modeling of surface fires, no link to fire effects, scale dependent, require specific fuels and forest structure, difficult to field test and validate, assume homogenous fuel conditions and adequate definition of the entire “cell,” simulated burns lack islands of unburned vegetation, and incorporate a limited number of spot fires.

Fire-effects models—A limited number of fire-effects models exist. They include CONSUME (Ottmar and others 1992), FOFEM (Keane and others 1994, Reinhardt and others 1996), empirical equations (Brown and others 1985), mechanistic models (Peterson and Ryan 1986), BURNOUT (Albini and Reinhardt 1995, Albini and others 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), limited focus on vegetation and fuels, high variation in reliability, scale dependency, difficulty in field testing and validation, and assumed homogeneous forest conditions and stand-wide burns.

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 from 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—More than 300 fire-history studies have been done in the United States and Canada since the 1940s. Most 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 having the most fire scars and where fire is relatively frequent. Subalpine and alpine environments have not been studied as often, and fire-history records often are incomplete. There also are 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). Three primary methods seem to be used to measure recent fire histories. Charcoal sediments in varve lakes provide 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). These are point records, however, 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 fire-disturbance records on the landscape. This means that a sincere effort must be made to identify, locate, measure, and analyze landscapes containing disturbance records, such as fire scars and forest stand development data. Field data, such as fire scars, in particular on stumps, will disappear after wild fires and prescribed fires.

Archival documents—Many sources of historical fire records 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. These records have some serious limitations, however: first, they are not consistently reported across agencies and geographical areas; second, most are not accurately defined spatially or are temporally inaccurate; and third, many of these documents are difficult to obtain, read, and enter into a standardized database or georeferenced database.

Photographic chronosequences—Past photo sequences provide a qualitative description of fire severity and extent (Gruell 1983, 1985). Photo series can be aerial photos, ground-based photos (orthophotos), or satellite images. The major limitation of these is 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 are 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 regime ages are often based on heights, and the maps often assume fire is the only disturbance. In addition, small polygons often are 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—Although 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 lake sediments are coarse-scale descriptions of fire occurrence (Clark 1988a,1988b; Clark and others 1996), but the estimates are useful only for identifying certain periods when large fires burned in close proximity to the area sampled (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

The biota includes all living things comprising an ecosystem. 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 will direct species-climate interactions. Indeed, fire creates conditions accelerating 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. Landscape-biota response to fire and climatic change will be less dramatic than stand-level responses, however. Future climatic and fire regimes will create some unique plant assemblages, perhaps even create communities that never occurred historically. Generalist species will initially predominate on future landscapes (Flannigan and van Wagner 1991, Shands and Hoffman 1987).

Simulation models—Many models 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), and FIRESUM (Kercher and Axelrod 1984). Other models include SIMFOR (habitat supply model), DISPATCH (Baker 1993), CRBSUM and LANDSUM (Keane and others 1996a), VDDT, and FVS (formerly PROGNOSIS; Wykoff and others 1982).

Conceptual models—Many conceptual and diagrammatic models are available that simplify the succession process. Most notable is the multiple-pathway approach of Noble and Slatyer (1977) and Cattelino and others (1979). Kessell and Fischer (1981) integrate 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) use these concepts for a simplified midscale succession model. Arno and others (1985) and Steele and Geier-Hayes (1989) integrate 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 additional 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, the Forest Service in particular, have extensive databases describing successional processes. Most databases have substituted space for time in their sampling strategies so that high geographic and site variabilities are inherent in the data. There are, however, some temporal data sets that go back 30 to 50 years. Stickney (1985) has a comprehensive temporal successional data set from western Montana.

Spatial data—Many sources of spatial data 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 airborne 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—Many studies have attempted to classify successional development after fire. See the annotated bibliography by Elliot and others (1993).

Autecological and synecological plant information—Abundant data on the response of plants to fire exist in the literature. 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 1992, Johnson and Larsen 1991, 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. Physiographic effects are probably applicable only to problems at small (up to a few hectares) to moderate scales (up to a few square kilometers), and their descriptions should be pertinent only to the issues at these scales.

Question 3: At what scales are processes important?

In questions 1 and 2, a context was provided for interpreting the relative importance of research and management needs in understanding and managing fire and ecosystems. This and the next two questions attempt to describe a working structure in which the research and management needs can be solved. The workgroup generated a set of responses to these questions that attempt to capture the important factors that should be included in any research or management project.

- Error propagation must be accounted for across scales. Assessing the accuracy of predictive models, spatial data layers, and collected field data is 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 spanning many scales is needed. Data sampling, storage, and analysis structures 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 databases. We need a ground-based sampling system that validates or tests simulation models so that the degree of error can be estimated. This task would be relatively difficult to accomplish.
- A scale of analysis 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). At the very least, the size of the analysis area needs to be triple the size of the largest disturbance to properly and meaningfully portray landscape dynamics and patchiness.

- 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 relations that are difficult to quantify through conventional means can be evaluated by 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 effectively.
- 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 might 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 links 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 that biological diversity is conserved. How do we preserve refugia (e.g., areas where fire should be excluded to protect wildlife) and still remain within acceptable thresholds? How many possible engineering solutions can one landscape have? 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 causing unacceptable disturbance consequences in one stand result in an overall improvement of conditions across the landscape? A method or tool 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 level of “resilience, plasticity, and hardness” of a landscape necessary to withstand, absorb, and incur disturbance, whether human caused or natural? We need to define the roles of exotic plants, animals, and fungi in ecosystems so that their impacts can be managed (Christensen 1990).
- Fire regime should be inferred from 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 representation 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 do 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 human-caused fire and fuels patterns and on the spatiotemporal conditions under which vegetation would act as a fuel break or a carrier of fire. Data also are needed on how fuel landscapes can be divided to limit or carry fire.

Question 5: What links 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 depend greatly 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 public.

- 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 also must provide the training, utility, and context for this knowledge. Researchers must make their results available to management. But research also should 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 and should be physically based. It is critical that EM projects have some quantification of fire severity to give them credibility 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 postfire 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 that 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. 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 21st 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?

Synopsis

The final listings of key questions, their responses, and rankings for each are given in table 2. The workgroup did not feel that it could make priority comparisons among the factors that impact fire disturbances because of the interrelated nature of those associations. Practicality of the key questions also was difficult to determine owing to tremendous uncertainties. In addition to the tabular information in table 2, the workgroup offered several general assessments of these links. First, besides the importance of the fire-disturbance factors listed, it is their interactions that are truly significant. This realization also is 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 the precipitating conditions, researchers can greatly assist managers. Third, the probability of large-scale disturbances, combined with cost, needs to be computed more reliably. For future needs, the workgroup noted that as fire suppression activities are reduced, in part due to cost and in part due to an ecosytem-management view of fire as an important natural disturbance, smoke management will become a central fire-management issue.

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Fire As a Large-Scale Disturbance[1]

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 spatiotemporal scales, modeling of 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 in both 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 generally are 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 climatic change on terrestrial ecosystems (Gardner and others 1996, Ryan 1991). The composition and function of ecosystems are constrained

[1] Workgroup members who developed this section: Carlos Avalos, Sarah Brace (Recorder), Joseph Fall, James Lenihan (Leader), David Peterson, and David Sandberg.

by disturbance, and ecosystem change often occurs as abrupt transitions owing 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 1990a,1990b), and changes in the frequency and severity of fire could be more important near-term determinants of rates of ecosystem change than are the 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 likely will shift from fire behavior and fire danger to the system-specific impacts of fire encompassed by the poorly defined concept of fire severity (Simard 1991). Unlike physical-based measures of fire behavior (e.g., rate of spread, fireline intensity) and the various indices of fire danger, broad-scale measures of fire severity would necessarily be system specific. Fire severity from the standpoint of the impact on ecosystems might be measured by the percentage of 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 percentage of area burned, in contrast to the fire frequency and return-interval statistics more appropriately applied at the scale of the tree or forest stand (Johnson and Gutsell 1994). The broad-scale relation 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 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 scales 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 levels. 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 (Heinselman 1985, Minnich 1983). 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 and thus influence the severity of subsequent events (Lotan and others 1985).

Implications for Modeling

To estimate broad-scale fire severity, it may not be necessary to model the impact of fire across all fire intensities and extents that occur on a landscape. The vast majority of fires, although 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. A combination of high temperatures and high winds 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 through 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 relation 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 (Bessie and Johnson 1995, Payette et al. 1989, van Wagner 1978), maritime coniferous forests of the Pacific Northwest (Huff and Agee 1980, Pickford and others 1980), and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) 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 percentage of moisture of the 1000-hour 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 by using existing fire spread and first-order fire-effects models (Keane and others 1994).

In broad-scale application of relatively fine-scale models, an adequate representation of the variation in model inputs due to landscape-level 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

by physiographic position, and to run the array of fire-behavior and fire-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 be specific even for 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 (fig. 4) dealt 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. Owing to the broad scope of these key questions, the workgroup felt that more specific and directed questions would better enable meaningful discussions. The workgroup therefore identified 17 focused questions for 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 descending order of importance. Responses were developed for the two or three most important focused questions under each key question. Each response was identified by its characteristic scope (i.e., global to local). The responses identified for a focused question were then ranked in importance. No rankings were developed for practicality aspects of any questions or responses. A summary of the importance ratings for key questions and responses appears in table 3.

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

Key questions and focused questions[a]	Importance[b]
1. What are the critical aspects of spatial and temporal <u>dynamics</u> of fire at large scales?	0.41
What characteristics of fire as a landscape-ecosystem disturbance are relevant to large-scale (spatial and temporal) <u>modeling</u>? 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 <u>climate</u>? What role will potential climatic change have on fire regimes? How will fire frequency control vegetation composition with climatic change?	0.25
What is the relative importance of the cumulative <u>impact</u> of small fires versus the impact of rare large fires or extreme events?	0.15

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

Key questions and focused questions[a]	Importance[b]
How do we deal with heterogeneity in modeling large-scale disturbance?	0.15
How important as refugia for fire-sensitive species are areas missed by fires over several events? 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 is appropriate fire regime defined 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 it be assumed that ignition sources are always available?	0.30
How important is fire size as a feature of the fire regime?	0.19

[a] Underlined words are used as a shorthand notation in analyses in tables 15-20, p. 72-74.

[b] The workgroup did not compare questions with respect to practicality.

Question 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 driving 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 effect 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 climatic change have on fire regimes? How will fire frequency control vegetation composition through climatic change?

- If climatic change results in long-term increased temperatures, this will result in an increase in fires, because it will affect the availability of fuels (regional, especially at northern latitudes).
- As ecosystems come under stress, a pulse of carbon will be released into the atmosphere from increased numbers and severity of fires (global).
- The relative impact of changes in fuels and climate will differ with 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 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 will accelerated carbon release) (forest biomes).
- Changes in fire regime will have a greater impact on northern-latitude ecosystems relative to carbon and nutrient cycling than on southern-latitude ecosystems (regional).
- Increased fire frequency will enable favorable 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 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?

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

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

Question 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 postfire 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 (as a regime and as individual events) affect 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 relations (regional).
- Fire accelerates biogeochemical processes (e.g., carbon flux) (global).
- Fire mobilizes stored carbon (distinct from other elements that 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 that share the same disturbance regime)?

Question 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 increasingly homogeneous, resulting in an increase in fire size (regional).

B. What characteristics of a fire regime have the most importance (provide value) to the public?

- 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 potentially may 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).

D. What are the relevant landscape and large-scale issues for political boundaries (management and policy differences)?

E. In a non-steady-state environment, how do you chose to manage for a particular landscape?

Question 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 east-side (dry) versus west-side (wet) ecosystems (e.g., in the Cascade Range 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 differs with 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?

Synopsis

Landscape-level changes resulting from fire are difficult to model owing to climatic and vegetation heterogeneity, lack of empirical data at large scales, and limited spatiotemporal scope of existing models. Because ecosystem composition and function change where disturbance regimes change, there nevertheless is a critical need to model large-scale disturbances. Because of time constraints, no practicality comparisons were made for any of the questions, and responses were generated only for the most important focused questions under each key question.

The workgroup felt that the broad key questions proposed in the straw man document (fig. 4) needed to be further refined. Focused questions were used to provide that refinement so that responses could be easily proposed. 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. 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, definitions of fire regimes for management objectives, large-scale issues for political boundaries, and management 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 ecosystem and landscape levels, there is much that needs to be better understood about fire as a large-scale disturbance if fire is to become part of future management strategies.

Fire-Effects Modeling Structures[1]

Background

The effects 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 1900s to describe and understand fire-effects, but the majority of the research has been conducted at the individual tree or stand scale, even though the results have been applied at larger spatial scales (McKenzie and others 1996a,1996b). For example, early fire-suppression policies that affected millions of hectares in the Western United States were based on fire-effects research at the stand scale (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 scale. 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

[1] Workgroup members who developed this section: Ernesto Alvarado, Mark Finney, Donald McKenzie, Carol Miller, Ronald Neilson, Lisa Snydal (Recorder), and David Weise (Leader).

predict fire ignitions, fire behavior, fire effects, and vegetation change in response to fire (see previous sections). 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 key questions directly addressed scaling and aggregation error, but 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 (e.g., crown scorch, cambial kill, tree mortality) but also to broader scale effects (e. g., altered successional pathways, vegetation mosaics, landscape dynamics).

Key Questions and Responses

The workgroup formulated 10 key questions, expanding on 3 of the questions in the straw man document (fig. 4) and identifying 7 others more directly related to modeling structures. Key questions were considered for importance, but not practicality. Workgroup members felt that key questions were too broad to enable them to make meaningful practicality comparisons. Key questions appear below in descending order of priority value. As time permitted, responses to the most important key questions were ranked by both importance and practicality. Bulleted lists following each key question 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 versus 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.

Question 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 structure of a model is part of the process.

- Analyze of the sensitivity of the internal components of a model to both data and interactions with other models. We also need sensitivity analysis of transitions among model components where there is spatial or temporal aggregation.
- Compare outputs of a model and model components to independent data.
- State the operational bounds for model inputs.
- Compare similar models to each other and with independent data.
- Compare model structures to structures from previously validated models. Disparate spatial and temporal scales of model application may, however, require different model structures.

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

Key questions and responses[a]	Importance	Practicality[b]
1. How does one validate a model's structure with respect to error propagation?	0.22	
We 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

Table 4—Key questions and their responses for fire-effects modeling structures are rated according to importance and practicality (continued)

Key questions and responses[a]	Importance	Practicality[b]
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; that is, it is 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 correct"	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 often are 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

Table 4—Key questions and their responses for fire-effects modeling structures are rated according to importance and practicality (continued)

Key questions and responses[a]	Importance	Practicality[b]
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 to be 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	

[a] Underlined words are used as shorthand notation in analyses in tables 21-27, p. 76-79.

[b] The workgroup did not compare questions with respect to practicality.

Question 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 by fire while nutrient losses occur at the watershed scale, and the consequences of immediate fire effects (tree mortality, etc.) 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.

- Modeling needs to be spatially explicit and temporally dynamic. Model resolution needs to be finer than the extent desired for projection.
- Spatial and temporal variability in weather and climate, vegetation, fuels, and fire behavior is different at different scales.
- The appropriate temporal and spatial resolution and extent need to be determined for each modeling effort.

- Considerations of temporal aggregations are as important as consideration of spatial aggregations.
- The structure of fire-effects models may be different at different spatial and temporal scales.
- Most existing data on fire effects have been collected and analyzed at small spatial and temporal scales.
- The magnitude of the error needs to be quantified relative to the scale of implementation.
- Models need to be designed to minimize errors at the intended scale of implementation.

Question 3: What are the desired outputs of an ideal fire-effects model?

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

- Produce spatially explicit and immediate fire-effects outputs and generate necessary inputs for successional vegetation models.
- Include physical and biological aspects so that the model has broad applicability; i.e., be process based.
- 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.
- Produce quantitative emission characteristics and time-dependent emissions.

Question 4: How does one calibrate a fire-effects model?

Calibration is crucial for accurate parameters in models so that the models 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 begin a model or sufficient data density to know the model is accurately representing the real world.

- Calibrate individual components of the model separately.
- To the extent possible, calibrate the model across the domain of the anticipated implementation.
- Calibrate against theoretical standards, so that calibration is more than a sequence of adjustments to make the output “look correct.”

- Maintain consistency of model resolution with the data resolution used for calibration.
- Calibrate against a large amount of data.
- Calibrate against another model.

Question 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 obtainable from the model.

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

Question 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 also will 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 (see question 3), will determine, to a great extent, the components of such a model. Responses to that question also are appropriate here.

Question 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, little effort has been made 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 periods and small spatial scales. Current large-scale assessment efforts (e.g., SNEP 1996 and the Columbia River basin assessment [Quigley and others 1996]) present an opportunity to validate and develop new fire-effects models for larger spatial scales. The main shortcoming to date is the lack of long-term data. The sites that have been maintained (e.g., 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.

Question 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 versus 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 change in response to a disturbance scenario, particularly fire, while retaining the fine-scale detail of fire-behavior calculations? One might use a series of simulations with transitions 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 of immediate fire effects and successional changes into a new unified model.

- System modularity should reflect process modularity.
- If model structure involves coupling independently developed models, internal consistency between analogous modules should be ensured and redundancy reduced.
- Where possible, process-based models are preferred over statistical models.
- The model should be structured in as modular a form as possible.

Question 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 over 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 from sparse networks of weather stations and must be interpolated for complex terrain while physical consistency is maintained among the weather variables. Also, many fire-behavior models and vegetation models operate at relatively short timesteps (subhourly 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 across complex terrain and from long to short timesteps.

Current tools for spatial interpolation range from geostatistical methods (e.g., kriging) to regression-based methods that explicitly incorporate topography (e.g., 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 members 1995).

Spatially explicit time series of potential future climates also must be developed to estimate fire effects in changing climates. Perhaps the most common approach for this is to use output from general circulation models (GCMs). The GCMs produce physically consistent weather output at timesteps of about 20 to 40 minutes over very coarse grids, for example, 4 to 5 degrees of latitude-longitude resolution. Because the grids are coarse, the global climate is simulated over a crude topography and does not adequately reflect the observed climate, particularly in mountainous regions. Future climatic scenarios therefore 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 members 1995). Such interpolation is done to carefully select and preserve temporal autocorrelation statistics produced by the GCM or existing in the baseline data.

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

Data gaps occur 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 often are not in a form useful for modeling; a high cost currently is 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.

Synopsis

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 as theses and dissertations or in the files of Federal and state land management agencies. Also, due to current societal concerns, other agencies (e.g., National Aeronautics and Space Administration, Department of Energy) are incorporating fire research into 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. Fire-effects models must be allowed, for example, to be wildly wrong. If basic model parameters are 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. 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. Any model thus can be used to identify knowledge gaps during the process of calibration.

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

From a strictly model-structure 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 the building of realistic models that include climate and other important factors.

We need to be conscious of intrinsic limits of the accuracy and precision of our knowledge and, therefore, the predictive ability of our models. 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[1]

Background

Good management rests on a foundation of solid science. Two challenges must be met to properly integrate management and science: First, research and management must collaborate through partnerships, and the key to this relation-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 a 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 descending order of importance (table 5). For each of the key questions, lists of responses are enumerated also in descending order of importance. The workgroup briefly discussed narrow- and broad-scope topics within each key question. These are summarized within the introductory paragraphs of the following sections.

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[1] Workgroup members who developed this section: Michael Hilbruner, Roger Ottmar, Lucy Salazar, James Saveland (Leader), Gordon Schmidt, Daniel Schmoldt, Robert Vihnanek, and Clinton Wright (Recorder).

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

Key questions and responses[a]	Importance	Practicality
1. What are the most useful model structures and outputs, to support issues in planning, operations, monitoring, and learning by resource managers, decisionmakers, policy-makers and researchers?	0.43	0.15
Design models 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 a 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.), and apply product life cycles	0.39	0.13
Standardize and provide desired user interfaces	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 sociopolitical 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

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

Key questions and responses[a]	Importance	Practicality
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

[a] Underlined words are used as shorthand notation in analyses in tables 28-35, p. 82-85.

Question 1: What are the most useful model structures and outputs to support issues in planning, operations, monitoring, and learning by resource managers, decisionmakers, policymakers, 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 many users. This question covers the specific and critical integration issues between model builders and model users.

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

A. Models should allow users to select fire regimes and show their probabilistic effects on the landscape. Although 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. The larger scale events that we observe therefore appear stochastic. Spatial and temporal patterns of fire occurrence, for example, affect a number of important landscape-scale 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 also are uncertain. Models consequently 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 many users, such as landscape planners, policymakers, and researchers.

B. 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 aware of which data can be readily and reliably collected by users. Otherwise, models will be unusable or, worse, used inappropriately with data for which the model was not designed.

C. Develop a 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 have been highly fragmented. For the manager to accomplish a specific task, a number of different models may be needed. Someone wishing to plan a prescribed fire, for example, might use fire-behavior models, 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—flows naturally, both conceptually and operationally. As the research and technology develop, 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 B).

D. Provide knowledge of model limitations to users and of user needs to model builders. Important concepts underlying a model and model structures need to be communicated to users. These concepts often limit what a model can do and how it should be used, and thus should be communicated in an easily understood way within the user documentation accompanying the model. Limitations inherent in a model also should be incorporated into the model's user interface so that those limitations can be expressed to users and 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, policymakers, 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 final response to the previous key question dealt with communication between model builders and model users to exchange model-critical information between them. Question 2 more generally addresses the communication environment during the model-development life cycle. This life cycle includes planning, design, development, testing, and delivery. Bidirectional communication is needed throughout this process, but how is an environment established that fosters such collaboration? Simply put, creating such an environment can succeed only if there are active, ongoing efforts to do so.

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

- Managers must assure the availability of researchers with needed expertise to address regional problems and questions.
- Regional issues must be accounted for in national research efforts.
- Better procedures must be built to allow managers and scientists to participate in the decisionmaking process.
- In a broader focus, communication with international researchers is an important issue.

A. Proactively seek opportunities to communicate. Many potential opportunities exist for model builders and users to communicate, such as coordinating data standards, establishing decisionmaking needs, setting important temporal and spatial scales, and dealing with nonpublic lands. But little will be accomplished until one group or the other takes the first step. Both groups must realize that they need to seek out the other on issues of mutual concern. Gatherings that are not project specific, such as regional workshops, can be used to bring everyone together for informal, generic discussions and to start planning 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.

B. Build long-term relations. Regional, multigroup collaborations tend to be open ended and, therefore, long term. 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 relations 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. Any significant project, no matter how specific, will often require a multiyear effort—not exactly short term. Additionally, project-specific applications can lead to other projects and eventually can attract other cooperators along the way. In a bandwagon sense, single-project collaborations 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, adjuncts, protocols, processes, and development climates are needed 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, 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.

A. 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. Models developed for research environments and with research needs in mind often are scant on information about how to apply them. Extensive documentation is required to use computer models properly. Documentation can include user manuals, tutorials, online help facilities, bug reports, example applications, technical reports, and peer-reviewed articles. All this helps to 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 or the Internet. These things, of course, put a tremendous burden on developers and an organization, so a high level of commitment is necessary to ensure that an information infrastructure is in place to accommodate these tasks.

B. Standardize and provide desired user interfaces. It is well accepted that, for most software users, the interface **is** the application; for example, 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-square-meter 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. To do that, we need to interact with a user interface that is, in effect, our sense of the application.

   An application must provide an interface (e.g., a graphic user interface) 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). Even though 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.[2] 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 consideration 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.

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[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

C. 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 and require time to evolve and develop. Also, supported information resources may not meet the needs of all users. In certain cases, needs of particular users may be unique and not readily satisfied with the current or planned information resources of an organization.

   These limitations of existing information-resources management mean that other avenues may need to be investigated to meet the needs. In some cases it may be more expedient to contract for data collection or data management, rather than assume large amounts of overhead to accomplish the same tasks inhouse. In other cases, model development and support may be 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 a large investment is made in internal resources.

D. Establish and support a development group. It has been suggested already that model builders and model users work closely together to build long-term relations. One particular form of long-term relation is a development group. Rather than working solely on a singular project of moderate-to-long duration, a development group can work on multiple projects as part of an ongoing relation. 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 needs of the users 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.

E. Apply free market principles (product development, support, and distribution). Marketing principles, as applied in the business world, can be borrowed and used 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; and second, 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 offered. A good model (or marketable product) will fall into disuse or will disappoint users if it is not supported. Followup service needs to target questions and problems the user is likely to have, 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). 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 also can target professional meetings catering to managerial concerns and applications, and demonstrations and workshops can 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 as 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 incorporation of social and political knowledge 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 they must be considered in concert with biological and physical components of the landscape. Human interactions are now part of the ecology of a landscape rather than exogenous to the biophysical ecosystem. Consequently, models and decision-support tools must have mechanisms allowing for the incorporation or consideration of 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.

A. 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 on 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. 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.

B. 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 frequently 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 that we currently are not aware of, and that we currently are 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 on social concerns is closely tied to ecosystem management, and hence it received special treatment. It also can 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 differ by situation. The following responses provide general guidance, however, on how to address interdisciplinary issues.

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

- Interaction of fire with threatened and endangered species of regional concern (e.g., northern spotted owl [*Strix occidentalis caurina*])
- 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 were (1) interaction of fire with threatened and endangered species, (2) regional haze generation and mitigation, and (3) effects of fire on carbon balance.

A. 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 should 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.

B. Involve a cross-section of managers and policymakers in model development. It should be 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 those of managers, both types of disciplinary specialists should be included.

C. Assign responsibility, develop measurement criteria, monitor accomplishments, and provide accountability for both research and management. A number of fairly specific things can be done to help incorporate interdisciplinary issues in models: (1) responsibilities for data collection or issue identification and description should be assigned to someone; (2) measurement criteria should be defined to establish what aspects of, and to what extent, a discipline is incorporated into a model; (3) research and management should periodically monitor accomplishments to determine whether work is progressing satisfactorily; and (4) 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 standards for success.

Synopsis

In general, the needs addressed by this workgroup include building more accurate, more inclusive, and more useful models, integrating models into decision-support tools, improving communication, and strengthening relations 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 additional aspects of fire behavior, such as lightning strikes, crown-fire ignition, and crown-fire spread. To assist with decision support, modelers and users must communicate effectively in developing models that address current management issues, such as social and political needs and biodiversity concerns.

Assessing the Effects of Fire Disturbance on Ecosystems

ANALYTICAL METHODS AND RESULTS

Analysis of Priority Vectors

Pairwise comparisons by workgroup members allowed us to generate priority vectors for the items being compared by using the principal right eigenvector method of Saaty (1980). These priorities may be for either “importance” or “practicality.” 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 two questions could be asked about the final priority vectors: (1) Was there general agreement among workgroup members on the rankings in the priority vector? and (2) Are different priority values in a priority vector really different? Answers to these questions could have a significant bearing on how the final rankings will be used to direct research on large-scale fire disturbance.

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. Given that, priority vectors can be generated separately from the judgments of each workgroup member. 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. This, however, locks in assumptions about the distribution of individual judgments and can result

in complicated statistical tests. Alternatively, we can assume that final priority vector elements are distributed normally and perform an analysis of variance (ANOVA) with posthoc tests for mean differences. One would not necessarily expect vector elements to be normally distributed, however; in fact, with a 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 apply distribution-free tests 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 before calculating statistics, so relative magnitude information is lost (SYSTAT 1992). This constitutes the conservative nature of these tests. The Friedman two-way ANOVA test analyzes the rankings by the different workgroup members for each set of items being compared (key questions or response, in our case). The null hypothesis is that there is no systematic variation in the rankings across items by workgroup members. The Kruskal-Wallis one-way ANOVA test indicates whether there are differences between the priority vector elements (i.e., key questions or responses), taking into account judgments of all workgroup members. The null hypothesis is that there are no differences. Although 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 posthoc test for mean differences. This test may not provide 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 pairwise 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 among individual responses. Results from these statistical tests nevertheless can discern some important differences in rankings. Analyses and conclusions by the workgroups appear in the following sections.

Analysis of Rankings

Links Among Fire Effects, Fuels, and Climate

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 agreed on their rankings of key questions or responses, (2) determine whether differences between rating scores for the key questions or responses were significant, and (3) identify which key questions or responses differed 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 for importance. A Friedman two-way ANOVA test rejected the null hypothesis ($p = 0.001$), indicating that judgments of workgroup members differed systematically; i.e., there was 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 also was highly significant ($p < 0.0005$), suggesting that real differences existed among the rating scores. A Wilcoxon signed-ranks test produced a matrix of pairwise probabilities (table 6) that indicated which of the key question importance scores in table 2 may actually be different. The highest ranked key question (factors [0.38]) was significantly more important than each of the other key questions, and the second highest ranked question (knowledge of fire [0.25]) was different from the two lowest-ranked key questions. There is no evidence to suggest that the two lowest-ranked key questions (management importance [0.08] and landscape [0.11]) were significantly different. This produced a three-level scale of importance for these key questions—with one question at the top, two at the bottom, and two questions between the others.

Responses—The number of responses differed 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, which were applied to the responses of each key question, appear in table 7. Only for the landscape key questions was 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 obscured individual response differences detected by subsequent tests. Still, for management importance and landscape key questions there seemed to be significant differences among 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 8 through 10. The highest ranked response (knowledge of fire [0.16]) for key question 2 (table 8) appears to rate as 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 among 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 [0.28]) differed from the four lowest ranked responses. With regard to management links, key question 5, the two highest ranked responses (public [0.17] and knowledge for management [0.17]) differed 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 range 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 for practicality, 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 practicality 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 management importance key question was there strong evidence to indicate

good agreement by workgroup members regarding rankings of the responses (Friedman test). There also was reasonably good agreement for the scales key question (0.083). For those same two key questions, there appear to be significant differences among rating scores for the different responses, as indicated by Kruskal-Wallis test probability values.

There were no apparent differences among responses to key question 2, due in large part to the lack of agreement by workgroup members. When we examined the Wilcoxon signed-ranks test for scale, the highest ranked response seemed to be different from the three lowest ranked responses at $p = 0.68$ (table 12). For question 4, adjacency, the highest ranked response for practicality, appeared different from two of the lower ranked responses, fire regime and fire breaks (table 13). Additional differences, however, were masked by low consistency scores. In the links to management key question, the workgroup felt that the two highest ranked responses, public and knowledge for management, are more easily attained than any of the other responses (table 14). This strong result reflects the high level of consistency in workgroup judgments, which is highlighted statistically in table 11.

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 related to 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 key question 2 (What ecological role does fire play at larger scales?) 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 history
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 history	.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 key question 4 (What are the critical characteristics of the fire-behavior environment?) 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	.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

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

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 key question 5 (What links are important to management?) 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	.116	1.000							
Biotic response	.500	.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 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 key question 3 (At what scales are processes important?) 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 level	.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 key question 4 (How are links related in a landscape context?) 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 key question 5 (What links are important to management?) for links among fire effects, fuels, and climate

Responses to key question 5[a]	Responses to key question 5[a]								
	Enabling	Technology	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.

Conclusions—Knowing the factors important to fire disturbance and knowing the links between them seem to be substantially more important than the other key questions (table 6). Key question 5, links 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 links; i.e., because the science contains large gaps, management issues cannot be intelligently addressed and, hence, are secondary.

Aside from particular exceptions noted above, responses within each key question were difficult to rank by importance or practicality. This most likely was due to the number of items being ranked (seven or nine in each case) and to the relative lack of consistency in judgment among workgroup members (tables 7 and 11). While each workgroup member's judgments were internally consistent, there was little agreement among members. This level of nonagreement strongly corroborates the feeling that links among fire effects, fuels, and climate are poorly understood and should be an important focus for future research and expanded modeling efforts.

Fire as a Large-Scale Disturbance

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 agreed on their rankings of questions or responses, (2) determine whether differences among rating scores for the questions or responses were significant, and (3) identify which questions or responses differed significantly. The next sections analyze separately the importance for the key questions, the focused questions, and the responses.

Key questions—Five workgroup members compared the four key questions appearing in table 3 with regard to importance. A Friedman two-way ANOVA test failed to reject the null hypothesis ($p = 0.115$), indicating that judgments of workgroup members may not differ systematically; i.e., there was 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 was significant ($p = 0.052$), suggesting that real differences existed among the rating scores for the different key questions. A Wilcoxon signed-ranks test produces a matrix of pair-wise probabilities (table 15) indicating 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 [0.41]) was significantly more important than the two lowest ranked key questions ($p = 0.068$ in each case). The second ranked key question (ecological [0.28]) fell 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 differed 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 was 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 appeared to be a significant difference among rating scores for the different focused questions, as indicated by the 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. Pairwise 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 was 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 among response ratings significant. The highest ranked response, aesthetics, appeared to be different (table 20) from 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 were significant.

Table 15—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 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 key question 1 (What are the critical aspects of spatial and temporal dynamics of fire at large scales?) 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 key question 3 (How can fire be managed at large scales?) 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 fire as a 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 focused question 2 (What characteristic of a fire regime has the most importance to the public?) under key question 3 (How can fire be managed at large scales?) 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 responses to focused question 2.

Conclusions—Although the workgroup offered few accordant 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 be accomplished initially by 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 management perspective.

Fire-Effects Modeling Structures

To ease the task of making comparisons, the workgroup logically divided the 10 key questions into two subcategories, one addressing model structure and application issues and the other, model data collection and use. Key questions within each subcategory were compared pairwise for 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 ANOVA test to discern differences in rankings for the key questions across the six workgroup members. The Friedman test rejected the null hypothesis (p = 0.002), indicating that judgments of workgroup members differed

systematically; i.e., there was good agreement on the rankings across workgroup members. A Kruskal-Wallis test for differences of mean rating scores for the key questions was also highly significant ($p = 0.001$), suggesting that real differences existed among the rating scores for the different key questions. A Wilcoxon signed-ranks test produced a matrix of pairwise probabilities (table 21) indicating which of the key question importance scores in table 4 may actually be different.

The highest ranked key question, validation, seemed to be significantly more important than most of the remaining key questions. It was 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, was 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 from lower scores are not substantiated owing 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. Overall agreement in rankings was supported by the Friedman test, but there were instances where excessive variation in ratings (and rankings) obfuscated more meaningful results.

Responses—Responses were generated for 6 of the 10 key questions as workshop time allowed. Five of these six constitute the most important questions. A statistical examination of ratings by workgroup members for responses within each key question appears in table 22. There was good agreement (Friedman test) by workgroup members on 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 was high, Kruskal-Wallis tests for mean differences in rating scores for the responses also were very significant. For the other key questions where there was less agreement among workgroup members, mean differences were less statistically significant.

Wilcoxon signed-ranks tests provide details about specific differences among response ratings for the key questions. We looked only at those key questions where workgroup members had good agreement in rankings (from table 22). For key question 1, validation, we found that the lowest ranked response, bounds, was very different from each of the other responses (table 23). The second lowest ranked response, compare to models, was different from the two highest ranked responses and from the lowest one. The two highest ranked responses, sensitivity and compare to data, were 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, a low-importance response, and two responses that fall in the middle. For key question 2, scale issues, there were few really strong differences among responses (table 24) owing to their number (eight) and their relatively similar magnitudes. The lowest ranked response, minimize errors, was different from most other responses. The highest ranked, fine resolution, was different from many of the lowest ranked responses, but not from the second lowest ranked one, quantify error. For key question 5, scale effects, the two responses were significantly different ($p = 0.038$).

Practicality rankings—Only responses to key questions were rated for practicality. 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, produced a relatively significant probability score, the lack of agreement across workgroup members caused most pairwise Wilcoxon signed-ranks tests to be not significant. A table of those values therefore is not provided here.

For the responses to key questions 2, scale issues, the least important response was also the least practical and seemed to be significantly less practical (table 26) than most of the other responses. The two most practical responses, variability and resolution and extent, were significantly different from the three least feasible ones. Because the practicality ratings in table 4 do not differ drastically for this key question, few of the other responses can be judged as different from either the most or least practical responses. For key question 4, calibration, the most important response, components, also was the most practical, and there was some statistical evidence to suggest that the practicality rating score for components was different from the three least practical responses (table 27). One of the least practical responses, domain, seems to be different from several of the more practical 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 inferred from the results.

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 components	Calibration	Validation	Climate	Scale effects	Structure	Model outputs	Data available	Data tools
Scale issues	1.000									
Model components	.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 6 most important key questions for 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 key question 1 (How does one validate a model's structure with respect to error propagation?) 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 key question 2 (What are the relevant spatial and temporal scale issues [including extent and resolution] related to modeling fire effects?) for fire-effects modeling structures

	Responses to key question 2[a]							
Responses to key question 2[a]	Resolution and extent	Minimize error	Quantify error	Variability	Small scales	Fine resolution	Temporal aggregation	Structure
Resolution and 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 6 most important key questions for 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 practicality-rating scores of responses to key question 2 (What are the relevant spatial and temporal scale issues [including extent and resolution] related to modeling fire effects?) for fire-effects modeling structures

	Responses to key question 2[a]							
Responses to key question 2[a]	Resolution and extent	Minimize error	Quantify error	Variability	Small scales	Fine resolution	Temporal aggregation	Structure
Resolution and 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 practicality-rating scores of responses to key question 4 (How does one calibrate a fire-effects model?) 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.

Conclusions—At the level of key questions, workgroup members were highly 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 practicality. Key questions dealing with validating model structure and incorporating relevant spatial and temporal scales for fire effects received high importance rankings by the workgroup as a whole. There also was 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 practicality rankings for responses to the second most important key question seemed to indicate that the second and third most important responses (variability and resolution and extent) also were quite practical. This has important implications for research program direction.

Managerial Concerns, Applications, and Decision Support

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 were significant differences among rating scores for the key questions or responses, and (3) identify which key questions or responses were significantly different. The next sections analyze importance and practicality separately.

Importance rankings—

Key questions—Six workgroup members compared the five key questions appearing in table 5. A Friedman two-way ANOVA test rejected the null hypothesis ($p < 0.0005$), indicating that judgments of workgroup members differed systematically; i.e., there was good agreement on the rankings across workgroup members. A Kruskal-Wallis test for differences of mean rating scores for the key questions also was highly significant ($p < 0.0005$), suggesting that real differences exist among the rating scores. A Wilcoxon signed-ranks test produced a matrix of pairwise probabilities (table 28) indicating which of the key question importance scores in table 5 may actually be different. There did not seem to be any evidence to suggest that the two highest ranked key questions (model structures [0.43] and communication [0.28]) were significantly different. These two key questions did differ significantly, however, from the other three questions. The third highest ranked key question (information transfer [0.15]) also appeared to be significantly different from the two lowest ranked questions (relevance [0.06] and socialpolitical [0.07]). 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.

Responses—The number of responses differed 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. For each key question there seemed, however, to be significant differences among rating scores for the different responses, as indicated by Kruskal-Wallis test probability values.

A few significant 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) showed a significant difference among their respective responses, Wilcoxon signed-ranks tests for differences of means failed 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 (table 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. All three responses appear to be significantly different from each other (table 32).

Practicality rankings—

Key questions—For practicality comparisons, only five workgroup members analyzed the five key questions appearing in table 5. A Friedman two-way ANOVA test marginally rejected the null hypothesis ($p = 0.057$), indicating that workgroup members tended to agree on their rankings. A Kruskal-Wallis test for differences of mean rating scores for key-question practicality was significant ($p = 0.017$), suggesting that real differences exist among the rating scores. A Wilcoxon signed-ranks test produced a matrix of pairwise probabilities (table 33) indicating which of the practicality scores in table 5 may actually be different. The highest ranked key question for practicality (communication [0.44]) was significantly different from the two lowest ranked questions (relevance [0.13] and sociopolitical [0.06]). The second highest ranked key question (information transfer [0.17]) was slightly above the $\alpha = 0.05$ threshold of significance ($p = 0.068$), indicating a difference from the lowest ranked key question (sociopolitical [0.06]). Otherwise, there were no other discernible differences among key questions for practicality.

Responses—Again, five workgroup members compared responses for each key question for 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 was there evidence to indicate good agreement by workgroup members regarding rankings of the responses (Friedman test). For three of the key questions, there did not appear to be significant differences among rating scores for the different responses, as indicated by Kruskal-Wallis test probability values.

When we examined the Wilcoxon signed-rank test for communication (the most practical key question), the two responses seemed to be very different, with proactively seeking opportunities to communicate being a much more practical response than building long-term relations (table 35). The only other key question containing any significantly different responses appeared to be question 3, information transfer. For this key question, there was some evidence (table 36) to suggest that free market principles is much less practical than standardizing interfaces and exploring other means for data management and technical transfer. No other significant differences were apparent for responses to these two key questions.

Table 28—Probability values generated by a Wilcoxon signed-ranks test for differences across means of the importance-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	.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 management concerns, applications, and decision support

Key question[a]	Friedman test probability	Kruskal-Wallis probability
Model structures	0.035	0.007
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 key 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?) 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 key question 3 (How can we rapidly and effectively transfer research information?) 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	.075	1.000			
User interface	.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 key question 5 (How can relevant interdisciplinary resource management issues be incorporated into models?) 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 practicality 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 key question 2 (How do we improve communication between users and model builders [scientists] relative to the development life cycle?) 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 key question 3 (How can we rapidly and effectively transfer research information?) 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.

Conclusions—Useful model structures and output to support decisionmaking were the most important issues for fire management. Improving communication between users and model builders also appeared to be a critical issue for management, applications, and decision support. There was relatively good agreement that proactively seeking opportunities to communicate is more important and more practical than building long-term relations. For the development and application of fire models, proactive 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 made communication a key factor for the application of large-scale fire-disturbance models to management and decision support.

In general, there was 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 which 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 man document (fig. 4) differed 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 also were highly consistent. The workgroup dealing with links among 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) and 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 links 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 that can be readily applied to large-scale fires or extrapolated from small to large scales. This leaves scientists and managers with two alternatives: initiate an intensive data collection effort with emphasis on large-scale fire, or 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 to anticipate 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 relations from small to large scales. It was emphasized that the most useful models will be those that are spatially explicit and temporally dynamic and where 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 links 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 simulate the effects of various fire regimes and management options on natural resource outputs and interactions. Effective user interfaces therefore 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 means of measuring combined importance and practicality. Second, one could select specific results from each workgroup, and use judgments from only certain members of each workgroup. The members whose judgments are used could change in each case (i.e., the 3-4 centroid vectors for each matrix could be used), or the judgments from the most knowledgeable 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 and 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 judgments by workgroup members 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 who 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 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. Although 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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Schmoldt, Daniel L.; Peterson, David L.; Keane, Robert E.; Lenihan, James M.; McKenzie, Donald; Weise, David R.; Sandberg, David V. 1999. Assessing the effects of fire disturbance on ecosystems: a scientific agenda for research and management. Gen. Tech. Rep. PNW-GTR-455. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 104 p.

A team of fire scientists and resource managers compiled scientific recommendations for future activities on (1) links 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. Although we clearly need more large-scale fire-effects data, it would be better to improve and link existing models that simulate fire effects in a georeferenced format while integrating empirical data as they become available. This effort should focus on improved communication between modelers and managers and on predicting the interactions of fire and potential climatic change at very large spatial scales.

Keywords: Analytic hierarchy process, ecological disturbance, fire effects, large-scale fire, modeling.

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