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Fire and aquatic ecosystems of the western USA: current knowledge and key questions

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Abstract

Understanding of the effects of wildland fire and fire management on aquatic and riparian ecosystems is an evolving field, with many questions still to be resolved. Limitations of current knowledge, and the certainty that fire management will continue, underscore the need to summarize available information. Integrating fire and fuels management with aquatic ecosystem conservation begins with recognizing that terrestrial and aquatic ecosystems are linked and dynamic, and that fire can play a critical role in maintaining aquatic ecological diversity. To protect aquatic ecosystems we argue that it will be important to: (1) accommodate fire-related and other ecological processes that maintain aquatic habitats and biodiversity, and not simply control fires or fuels; (2) prioritize projects according to risks and opportunities for fire control and the protection of aquatic ecosystems; and (3) develop new consistency in the management and regulatory process. Ultimately, all natural resource management is uncertain; the role of science is to apply experimental design and hypothesis testing to management applications that affect fire and aquatic ecosystems. Policy-makers and the public will benefit from an expanded appreciation of fire ecology that enables them to implement watershed management projects as experiments with hypothesized outcomes, adequate controls, and replication.

Keywords: Wildfire; Fire and fuels management; Conservation; Restoration; Aquatic and riparian ecosystems

1. Introduction

Fire was arguably the most important forest and rangeland disturbance process in the western USA for many millennia (Covington et al., 1994; Hessburg and Agee, this issue). Along with insects, diseases, and weather disturbances, fires were as much a part of the western landscape as the plant and animal species that lived there. Fires were primarily responsible for creating and maintaining range and variation in the spatial patterns of forest and rangeland habitats. Two centuries of settlement, natural resource management, and

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climate variation have transformed the fire regimes, vegetation and fuel patterns, and overall functionality of western forests. Despite the efforts to prevent and suppress wildland fires, fire nonetheless revisits western landscapes at irregular intervals—sometimes with catastrophic effect, sometimes not. The primary question before managers and policy-makers is not whether fire suppression efforts should be strengthened. Wildland fires will continue to burn despite suppression attempts. The question before public land managers and policy-makers is: "How might we influence the timing, severity, and pattern of wildland fires to achieve land, water, and ecological management goals?"

Recent large fires, losses of life and property, and concerns about forest health in the western USA have resulted in new initiatives to reduce the threat of large "catastrophic" wildfires, such as the President's Healthy Forests Initiative (The White House, 2002). Terrestrial ecologists and forest managers also hope to restore more natural patterns and variation of forest structure, composition, and related processes. The National Fire Plan (USDA, 2000, hereafter, the Plan) provides guidance for an interagency approach to fire and fire-related management. The goals of that Plan are to ensure fire-fighting capability, reduce fuels in high-risk areas, rehabilitate fire-damaged sites, and protect vulnerable communities and property. A primary focus of the Plan has been to reduce the risk of destructive wildfire, particularly at the urban–wildland interface, by fire suppression and fuels reduction. The 2001 Federal Wildland Fire Management Policy, a key part of the National Fire Plan, also states that the role of wildland fire as an essential ecological process and natural change agent will be incorporated into the planning process. Understanding the role of fire and the effects of fire-related management on aquatic and terrestrial ecosystems is integral to that effort.

Increased concern over high-severity fires comes at a time when considerable effort is also focused on conserving sensitive fish and amphibian species and restoring networks of productive aquatic habitats. Many believe that large, severe wildfires pose additional risks to threatened species throughout the western USA; therefore, an aggressive program of active management is needed to reduce those risks (Williams, 1998; Babbitt, 1999; Haftl, 1999; Snyder, 2001). This opinion is not uniformly accepted (Andersson, 1998; DellaSala and Frost, 2001; Rieman et al., this issue). Wildfire, fuels management, and fire suppression activities can all alter aquatic and riparian ecosystems. Although land management activities often have resulted in negative effects to aquatic and riparian ecosystems (Rieman et al., this issue), fire can be important for the maintenance of complex and productive habitats (Reeves et al., 1995).

Most information used to assess or predict the effects of fire and fire-related management comes from theory, post-wildfire studies, and literature on the effects of forest management on streams and riparian areas (Meehan, 1991; Naiman et al., 2000). Although there have been some attempts to synthesize information on particular fire-related topics (see Gresswell, 1999), there is no widely available synthesis specifically focused on issues of fire and fire-related management relevant to aquatic and riparian ecosystems. Furthermore, several of the action items in the National Fire Plan have not been fully tested and their ecological consequences are uncertain.

The purpose of the Fire and Aquatic Ecosystems Workshop was to synthesize existing information, identify concepts and tools emerging from current science, explore research strategies that will improve our understanding, and identify management implications. The ultimate goal was to help managers identify ecologically sound and socially acceptable ways to protect and restore aquatic ecosystems and processes that are influenced by fire and its management. In this paper, we summarize the important points that emerged from the workshop and related research. From this foundation, we suggest several key points for future management. We also suggest research questions that, when answered, will aid in formulating socially and ecologically acceptable fire management policies, and we propose a path toward improved understanding that involves managers, scientists, and the public.

2. Ecological foundation

Many of the papers in the workshop focused on physical processes that influence the characteristics of habitats in aquatic ecosystems and their linkages to fire, terrestrial landscapes, and climate (Benda et al., this issue; Hessburg and Agee, this issue; Meyer and

Pierce, this issue; Miller et al., this issue; Spencer et al., this issue; Wondzell and King, this issue; Whitlock et al., this issue). Others considered aquatic ecological processes in the context of the preceding discussions (Dunham et al., this issue; Minshall, this issue; Pilliod et al., this issue; Rieman et al., this issue). From these papers and existing literature, two concepts emerged as important elements of an ecological foundation for managing fire and aquatic ecosystems: (1) watersheds their associated aquatic habitats and species' populations are dynamic and adapted to disturbances such as fire and related post-fire processes; and (2) climatic patterns had, and will have, a profound influence on terrestrial and aquatic ecosystems, fire and other disturbance processes, and their interactions.

2.1. Landscapes are dynamic and fire plays an important role in structuring aquatic ecosystems

We often speak of terrestrial and aquatic ecosystems as though they are separate, but aquatic ecosystems are structured by interactions among terrestrial and aquatic processes and climate. Wildfires influence hillslope erosion, stream sedimentation, and large woody debris recruitment to streams (Benda et al., this issue; Miller et al., this issue; Wondzell and King, this issue). The timing and severity of erosion and sedimentation differ by geography, geology, precipitation regime, and fire regime. Fire-related erosion and sedimentation can occur chronically and episodically. Chronic erosion tends to deliver fine sediment over long periods, typically in the absence of re-vegetation or from roads and fire lines. In contrast, pulses of sediment and large wood are delivered to streams by post-fire landslides and debris flows. Over time, wood and sediment are routed downstream by fluvial processes that form aquatic habitats (Reeves et al., 1995; Benda et al., this issue; Miller et al., this issue; Minshall, this issue). Coarse sediment and wood are gradually depleted as they decay, break up, and are transported downstream until replenished by new post-fire erosional episodes (Benda et al., this issue; Miller et al., this issue). The dynamics of aquatic habitats are largely driven by topography, climate, and the pattern of disturbances such as fire and large storms.

Disturbances, whether caused by fire, storms, or volcanic eruptions are important to the natural history of aquatic ecosystems (Reeves et al., 1995, 1998; Bisson et al., 1997; Benda et al., this issue; Meyer and Pierce, this issue). The biodiversity in many aquatic ecosystems is shaped by patterns of disturbance (Reeves et al., 1995; Naiman et al., 2000; Rieman et al., this issue). As disturbances create a dynamic mosaic of habitats, a variety of species, life history strategies, and phenotypes persist within watersheds (Southwood, 1977; Healey and Prince, 1995; Reeves et al., 1998; Naiman et al., 2000; Dunham et al., this issue; Rieman et al., this issue). Species diversity, life history diversity, and phenotypic plasticity are mechanisms that allow communities and populations to adapt to variable and changing environments, or conversely, are a manifestation of the diversity and dynamic nature of aquatic habitats (Gabriel and Lynch, 1992; Gresswell et al., 1994; Whitlock, 1996; Reeves et al., 1998; Dunham et al., this issue).

Although it is possible to alter fire patterns by directly managing fuels and by fire prevention and suppression activities, we can never eliminate the occurrence of large disturbances nor is it clear that we should. Management actions that attempt to eliminate natural disturbances or fail to acknowledge the dynamic nature of habitats by emphasizing spatially or temporally fixed goals or "optimal" habitat conditions are likely to be ineffective, subject to unexpected outcomes and uncertain ecological trajectories (Reeves et al., 1995; Bisson et al., 1997; Beechie and Bolton, 1999; Poole et al., 2001; Roni et al., 2002; Rieman et al., this issue).

Periodic large-scale disturbances of aquatic ecosystems are inevitable and often beneficial over long periods, and this knowledge can form an important ecological foundation for fire-related management. A dynamic view diverges from the more traditional idea that aquatic ecosystems should be managed as stable or static systems to be perpetually maintained for select species. The latter strategy attempts to protect against aquatic disturbance everywhere all of the time (within human capabilities), but the dynamic view accepts patterns of disturbance and recovery across a landscape as a process needed for an interconnected mosaic of diverse, changing habitats and communities.

2.2. *Climate changes will affect fires, fire management options, and aquatic habitats*

Climate variation is often overlooked when considering changing land cover and fire patterns, but in reality, variation over decades, centuries, and millennia is substantial. Cyclic decadal-scale oceanic and atmospheric patterns are well known and continuously monitored, e.g. El Nino–La Nina cycles, the Pacific Decadal Oscillation, and the North Atlantic Oscillation (Dettinger et al., 1998; Hare and Mantua, 2000; Mantua et al., 1997; Swetnam and Betancourt, 1990, 1992, 1998; Veblen et al., 2000). Even longer-term climate changes have been noted in paleoecological studies. It is apparent that significant warming has occurred at least three times in the last 400,000 years (Webb III and Bartlein, 1992; Petit et al., 1999), although the current warming may be made more severe by anthropogenic inputs of greenhouse gasses (Houghton et al., 2001).

Climate change profoundly affects processes that create and maintain aquatic habitats. Some effects are direct, particularly those involving water yield, peak flows, and stream temperature. Other effects occur indirectly as climate change forces alteration of the structure and distribution of forest communities and the characteristics of wildfire. There is a sizeable effect of climate variability on stream hydrology (Jain and Lall, 2001; Poff et al., 2002) and geomorphic processes (Schumm and Hadley, 1957; Bull, 1991; Meyer et al., 1992; Pederson et al., 2001). Such changes can happen over relatively short time scales (10–100 years), and decadal-scale climate regime shifts can have greater influence on stream flows than the management practices we are often most concerned about (Jain and Lall, 2001). Climate variability affects fire occurrence, with more frequent and larger fires associated with warmer, drier regimes (Swetnam and Betancourt, 1990, 1998; Whitlock et al., this issue; Meyer and Pierce, this issue). With continued warming, large fires and substantial changes in forest vegetation may be anticipated whether current fuel accumulations are reduced or not (Morgan et al., 2001; Whitlock et al., this issue).

At broad spatial scales fire size varies with fire regimes (Agee, 1993, 1998); however, most forest fires burn less than one hectare (Pyne, 1984). Strauss et al. (1989) reported that 1% of forest fires accounts for 80–96% of the total area burned. Size and severity of individual fires are directly related to physical and climatic variables that influence the spread and intensity of fire, and the pattern of burn severity can vary with daily fire size (Turner et al., 1994). When fires are small, pattern is less predictable and more heterogeneous, and at this scale, the controlling variables included fuel moisture, fuel type, atmospheric humidity, wind, temperature, and topography. When fire size increases, the main controlling variables are wind velocity and direction, the pattern of burn severity is highly predictable, and heterogeneity decreases (Turner et al., 1994). Large fires are generally related to prolonged periods of extreme dryness (Schullery, 1989).

There are at least three important climate-related issues that bear on land and aquatic management decisions. First, dynamic hydrologic simulations (e.g. Miller et al., this issue) must relate the sensitivity of models (and the inferences we draw from them) to assumptions about climate change and low-frequency climate variability (e.g. decadal-scale fluctuations). Second, the debate over management actions must recognize that both climate history and human development have contributed to changes in forest conditions and wildfire dynamics (Hessburg and Agee, this issue; Whitlock et al., this issue). Finally, knowledge of pre-fire suppression conditions and historical vegetation and fire patterns will be updated as alternative future climate scenarios are considered (Whitlock et al., this issue).

The last two points are particularly relevant for management focused on fire and fuels. Hessburg and Agee (this issue) discuss spatial patterns of vegetation, fuels, and fire behavior for fire tolerant forests, based on reconstructions of past conditions that used a space-for-time substitution algorithm. Historical information on vegetation and fire patterns using this approach or one using a fire regime approach (Cissel et al., 1998, 1999) include the effects of several centuries of climate-fire-vegetation interaction and significant climate variability. This information is useful to illustrate the problems that currently exist, but a return to historical forest patterns may not be possible under some future climate changes. This is especially true of climate regime shifts that exceed the variability of the historical climate for which range and variation in vegetation and fire patterns have been characterized. The type of forest that naturally occurred in a particular location in the early 20th century may or may not be compatible with the fire regimes of an altered climate (Whitlock et al., this issue). It is, therefore, useful to characterize the range and variation in forest vegetation and fire patterns for the preceding climate period to provide a benchmark for assessing the direction, rate, and magnitude of changes caused by climate and development. Those ranges may be just a beginning point for interpreting future forest development and management trajectories.

3. Key points for management

Understanding that landscapes and aquatic ecosystems are dynamic and strongly interconnected provides an important context for fire-related management. Implementation of these concepts, however, has few precedents and remains problematic. We believe that effective integration of fire and ecological management is possible and desirable. The following are key points based on our current understanding of the linkages between fire, landscapes, and aquatic ecosystems that provide a foundation for progress.

3.1. Active management of fire and fuels to restore resilient and diverse ecosystems should incorporate a full spectrum of ecological patterns and processes

The National Fire Plan (USDA, 2000) emphasizes management of fire and fuels. A major premise of the Plan and the Cohesive Strategy (Laverty and Williams, 2000) is: "... that sustainable resources are predicated on healthy, resilient ecosystems." An implied management goal is to restructure forest and rangeland conditions so that wildfire severity is reduced and fire can be reintroduced as a positive agent of change. The implementation of aggressive fire and fuels management has begun. Although such activities may affect wildfire behavior under some conditions, the more challenging goal of restoring or developing landscapes and ecosystems that are resilient to disturbance (Ludwig et al., 1997) remains elusive. Long-term restoration of the physical and ecological processes important to maintain diverse terrestrial and aquatic ecosystems requires strategies that go beyond simply treating fuel accumulations or attempting to prevent high-severity fires. Perhaps the most effective means to ameliorate negative consequences of fires on aquatic systems is to protect the evolutionary capacity of these systems to respond to disturbance. This strategy would focus on protecting aquatic communities in areas where they remain robust and restoring habitat structure and life history complexity of native species where feasible (Gresswell, 1999).

Ecosystem-based management incorporates spatial and temporal patterns. Landscape patterns of living and dead trees influence crown fire potential and fire behavior (Baker, 1989, 1992, 1993, 1994; Shinneman and Baker, 1997; Hessburg et al., 1999a,b, 2000). Current evidence suggests that some forest landscapes have changed extensively in their spatial patterns of living and dead vegetation. When changes in climate are considered, the likelihood that high-severity fires will occur in many large forested areas has increased dramatically over the last century (Agee, 1998; Hessburg and Agee, this issue). In some areas, human settlement and management have created larger, more contagious patterns of vegetation that are prone to high-severity fires. In others, development has led to a highly fragmented landscape dissected by roads where opportunities for accidentally caused fires have increased. Historical landscapes represented a more complex patchwork of fire regimes than those at present. Restoration of resilient forest ecosystems will require restoration of more natural patterns of forest structure, composition, and fuels, not simply a reduction of fuels and thinning of trees. Natural patterns of structure, composition, and fuels can be determined from estimates of historical range and variation, projected from succession and disturbance simulations (e.g. Keane et al., 2002), and those involving climate changes. To produce resilient forest ecosystems, it will be important to restore synchrony between landscape patterns of forest vegetation and the fire regimes that would naturally occur under the current and projected future climate regimes.

Just as effective forest restoration requires a landscape approach that is sensitive to spatial and temporal pattern, restoring degraded aquatic ecosystems requires a similar perspective. A central message emerging from the convergence of landscape and aquatic ecology in the last decade (and one strongly echoed in the workshop) is that to conserve or promote resiliency in ecosystems, we must focus on conserving and restoring the physical and biological processes and patterns that create and maintain diverse networks of habitats and populations, rather than engineering the condition of the habitats themselves (Ebersole et al., 1997; Frissell et al., 1997; Gresswell, 1999; Naiman et al., 2000; Benda et al., this issue; Minshall, this issue; Rieman et al., this issue). This implies minimizing constraints on habitat potentials and the expression of life cycle diversity of aquatic species that are native to these habitats. Ecosystem-based management attempts to restore: (1) natural patterns in the timing and amount of stream flows (Poff et al., 1997); (2) production and delivery of coarse sediment and large wood to stream channels (Reeves et al., 1995; Beechie and Bolton, 1999; May and Gresswell, in press; Meyer and Pierce, this issue); (3) the function of riparian communities as sources of organic matter, shade, and buffering for streams (Gregory et al., 1991); (4) connections among streams, their floodplains, and their hyporheic systems (Naiman et al., 2000); and (5) habitats required for the full range of life histories, gene flow, and demographic support among populations (Healey and Prince, 1995; Gresswell et al., 1994; Rieman and Dunham, 2000; Poole et al., 2001; Roghair et al., 2002; Dunham et al., this issue; Rieman et al., this issue). This management approach attempts to maintain forests and aquatic ecosystems that can respond to and benefit from inevitable disturbances such as fire, rather than eliminating the threat of the disturbance itself.

Logical priorities for restoration activities emerge from an evaluation of the changes and constraints (e.g. Beechie and Bolton, 1999; Luce et al., 2001; Pess et al., 2002), and the probable efficacy of the proposed action (Kruse et al., 2001; Roni et al., 2002). Habitat loss and fragmentation, channelization, chronic sediment inputs, accelerated erosion, and changes in hydrologic regime (NRC, 1996; Lee et al., 1997) are problems that merit consideration. Restoring physical connections among aquatic habitats, however, may be one of the most effective and efficient first steps to restoring or maintaining the productivity and resilience of many populations (Rieman and Dunham, 2000; Roni et al., 2002). If that cannot be done, eliminating the threat of disturbance, by fire or otherwise, may be insufficient to prevent local population extinctions in many streams (Dunham et al., this issue; Rieman et al., this issue). The National Fire Plan places a major emphasis on managing fire and fuels. A similar plan for restoring important patterns and processes that govern terrestrial and aquatic ecosystems is needed.

3.2. Spatially explicit strategies for management that incorporate the risks and opportunities for conservation and restoration of aquatic ecosystems are important

Ecological changes in forest and aquatic ecosystems caused by fires vary across the western USA. Physiographic constraints, physical and biological recovery processes, and the local fire regime vary from site to site. Landscape context is important in defining the issues and the opportunities for fire-related management (Rieman et al., this issue).

A strategic approach to fire and fuels management will be important from terrestrial and aquatic perspectives. Resources are limited and the challenges are great; fuels treatments and forest restoration activities cannot occur everywhere they might seem needed. Watersheds also are not necessarily of equal importance from either fire-fuels or ecological perspectives. The National Fire Plan and subsequent Cohesive Strategy recognized these problems and established general priorities for fuels management activities. High priority areas include the urban–wildland interface, readily accessible municipal watersheds, threatened and endangered species' habitats, and forests that are currently at low wildfire risk but are prone to change.

The urgency to protect human life and property and the infrastructure of human communities will ordinarily take precedence. We cannot expect management to emphasize activities that primarily benefit aquatic ecosystems in the urban–wildland interface, although efforts to mitigate the effects of roads or other management-related activities on aquatic ecosystems could still be useful. The need to coordinate fire and fuels management with aquatic conservation objectives will be greatest where the habitats for sensitive species occur in more remote forests that are prone to uncharacteristically severe fires.

Conflicting objectives are often rooted in uncertainties regarding tradeoffs between fire and fuels management and the long-term ecological risks and benefits of fires we attempt to avoid (Rieman et al., this issue). There are potential risks and benefits associated with any management action. In some cases these are clear, but in most cases they are not. Recognizing the importance of continually learning from results of management actions, and adjusting when necessary, is critical in situations where managers implement activities with highly uncertain consequences (Walters, 1986).

Important changes in the nature of fire appear to be most pronounced in forest types that historically supported low and mixed severity fires prior to Euro-American settlement (Hessburg and Agee, this issue; USDA, 2000). The potential for large fires emerges as much from the continuity of high fuel levels that now exist across contiguous forest types as from the expansive area affected by forest changes (Covington et al., 1994; Skinner and Chang, 1996; Hessburg et al., 2000). By working strategically and concentrating on accessible sites, it may be possible to break up high-risk fuel continuity. Because forest changes important to fire and fuels management are most strongly associated with lands that have been previously roaded and intensively managed in the past (Covington et al., 1994; Huff et al., 1995; Hann et al., 1997; Rieman et al., 2000; Hessburg and Agee, this issue), few new roads may be needed (USDA, 2000). Roads have caused some of the most chronically damaging management impacts on aquatic ecosystems to date (Lee et al., 1997; Jones et al., 2000; Trombulka and Frissell, 2000; Rieman et al., 2000).

The location and sensitivity of watersheds can help guide the process of setting priorities for management actions. From an aquatic conservation perspective, priorities for active vegetation and fuels management occur in the following areas:

1. Watersheds where the threat of large fire is high and local populations of sensitive aquatic species are at risk because they are isolated, very small, or vulnerable to invasion of exotic species (Kruse et al., 2001; Dunham et al., this issue). This may be the case in many of the interior river basins of western USA, but perhaps less so in the Pacific Northwest (Rieman et al., this issue). In highly sensitive areas, the first priority for conservation management is easing existing constraints on population recovery, e.g. by restoring connectivity among patches of favorable habitat (Dunham et al., this issue; Rieman et al., this issue). Where that is impractical, active management to reduce the impact of fires and fire suppression actions could be an important short-term conservation strategy (Brown et al., 2001; Rieman et al., this issue).
2. Watersheds where there is not much to lose, but a lot to gain. In some watersheds, habitat degradation has been extensive and remnant populations of native species are severely depressed or even locally extinct. Watersheds that have been heavily roaded and influenced by intensive management in the past may contain forests in a condition of high fire vulnerability (Rieman et al., 2000; Hessburg and Agee, this issue). Existing road systems can be used to facilitate understory vegetation and fuels reduction, and subsequently removed or renovated to re-establish hydrologic and biological connectivity (e.g. Roni et al., 2002). The short-term risk of ground-disturbing silvicultural activities related to vegetation and fuels reduction may be offset by the potential long-term benefit of reconnecting and expanding habitats and populations. In the long term, ongoing treatment with fire may be needed.
3. Watersheds in which aquatic biodiversity and sensitive species are of limited significance. Because the vulnerability of dry and mesic forests to high-severity fire is frequently associated with lands that have been intensively managed in the past (e.g. low-elevation portions of the Columbia River Basin), the need for active fire and fuels management now may be greatest in areas where aquatic ecosystems have been significantly altered (Rieman et al., 2000) and conservation or restoration of the entire suite of native plants and animals may be impractical. These are logical places to experiment with active management where learning can proceed without taking unacceptable risks (Ludwig et al., 1993).

These priorities reflect concerns associated with at-risk fish and other aquatic species and with opportunities to coordinate fire and aquatic ecosystem management planning. However, they do not represent all possible situations; for example, there will be locales where aquatic species are healthy and habitats remain productive, diverse, and interconnected, but also where active fire and fuels management is deemed important (Rieman et al., 2000). From an aquatic conservation perspective immediate intervention may not be needed, because populations will be the most resilient to disturbance. But intervention could encourage development of a more natural and diverse forest structure whose response to fires and other disturbances helps maintain aquatic productivity over time (Reeves et al., 1995). In such instances, careful planning and a commitment to long-term monitoring of treatment and control sites is important for validating assumptions about the efficacy of fire management activities.

Similar priorities and arguments can be made regarding emergency post-fire restoration. Although it is widely acknowledged that there is uncertainty about the effectiveness of some rehabilitation measures (Robichaud et al., 2000), there is less discussion about where it might not be useful or possibly even detrimental. Watershed disturbance from fire-related flooding, sedimentation, and woody debris inputs may be as important to aquatic ecosystem integrity as fire itself is to forested landscapes. Under what conditions is it appropriate to apply burned area emergency rehabilitation (BAER) to watershed restoration? Some of the priorities listed above apply. For example, there may be no compelling case to attempt emergency restoration for ecological purposes where aquatic communities remain diverse, habitats are well connected, and watersheds are generally intact. However, where populations are small and habitats are fragmented and degraded, continued disturbance could be a threat. In some cases, it could be important to mitigate the risk of substantial erosion using emergency rehabilitation measures. In other cases, large wood and coarse sediment recruited to streams through erosion may actually be needed to create productive habitats. In any case, large-scale experimentation that tests BAER treatment effectiveness is needed to understand the utility of these rehabilitation activities.

3.3. Coordination and a common conceptual foundation are important in the management and regulatory process

Integrated management of forest and aquatic ecosystems has proven difficult. Success may be constrained in part by differing perceptions about the role of fire, the effects of management, and the temporal and spatial scales of the processes influencing critical habitats (Rieman and Clayton, 1997; Rieman et al., 2000, this issue). Essentially, managers hope to move quickly to mitigate the threat of uncharacteristically severe fires and their anticipated effects. Regulators concerned about aquatic resources fear that the effects of management (e.g. soil disturbance, road building, and increased erosion) may represent a greater threat to aquatic ecosystems than the fires themselves. The establishment of clear restoration objectives may be confounded by differing organizational missions and cumbersome approaches to coordination (Samson and Knopf, 2001; Rieman et al., this issue). Development of common goals and a consistent conceptual foundation will be important for progress.

Large land management organizations are multidisciplinary in nature and attempt to seek a reasonable path through seemingly competing natural resource objectives. This often leads to conflict and compromise, but sometimes to innovative approaches (e.g. Cissel et al., 1998, 1999). Management plans generally are not optimized for a specific resource or species and are sometimes hypothetical or experimental in nature. Tension often exists within an agency because one resource issue may dominate or be constrained by others (fire and fuels versus aquatic resources; see Rieman et al., this issue). Individual resource-oriented regulatory agencies, in contrast, address a smaller subset of issues dictated by law. Because populations, habitats, and water quality have been harmed by previous management activities, future activities are also assumed to be harmful. In some organizations, this has led to a skeptical view of active management. Different beliefs in the value of active management have yielded intense frustration (USDA, 2002).

The threats posed by large fires and by management to prevent or suppress those fires are real, but vary in their relative significance for aquatic ecosystems based on the unique biophysical context of each location (Rieman et al., 2000, this issue; Hessburg and Agee, this issue). There are clearly risks to be minimized, but there are also significant opportunities for improvements in terrestrial and aquatic conditions. Two problems pose important barriers to achieving this integration: (1) lack of coordination in planning and consultation; and (2) lack of a broad ecosystem perspective.

The coordination of fire and fuels management is intended to support the restoration and maintenance of resilient and productive ecosystems including those critical to threatened and endangered species. The urgency to reduce the threat of large fires, however, means that consideration of aquatic resource values is often a reactive rather than proactive process. As a result, inclusion of aquatic considerations may be seen as a constraint on fire and fuels management options rather than an integral part of broader ecosystem management. Objectives guided by the National Fire Plan, including fire and fuels management projects, may conflict with those developed under the Endangered Species Act (EST) and resulting species recovery projects. Integration occurs through the process of consultation, often after projects are well underway (Rieman et al., this issue). Planning and consultation efforts that are coordinated from the start and emerge from consideration of spatially and temporally explicit objectives for both terrestrial and aquatic ecosystems are likely to improve restoration effectiveness. For example, watershed-scale wild and prescribed fire behavior analysis would be invaluable to setting spatially explicit objectives.

Interpretations of the Endangered Species Act, various air and water air standards, and efforts to expedite the process of consultation, have largely been attempts to control management-related disturbances by specifying acceptable activities and by identifying standards for environmental conditions that result. For instance, the Total Maximum Daily Load (TMDL) approach to water quality management set by the Clean Water Act seeks to keep streams within acceptable limits, essentially at all times. Similarly, aquatic habitat targets (e.g. NMFS, 1999) used to satisfy ESA recovery goals imply that all streams should have ideal habitat at any particular time. These approaches fail to acknowledge that ecosystems are dynamic and that disturbance and change, even if resulting in short-term habitat degradation, may be required to create productive habitat conditions and resilient populations over time (Reeves et al., 1995).

A dynamic view of landscapes and ecosystems is articulated in the National Fire Plan, and in direction for implementing the ESA (NMFS, 1999), and recent reviews of water quality criteria (Poole et al., 2001). The perception that any disturbance resulting from management or natural causes is a threat, however, is perpetuated in the actual implementation of many of these programs. By concentrating on fixed environmental standards rather than on the spatially and temporally varying processes that constrain, create, and maintain aquatic habitats and populations (e.g. Beechie and Bolton, 1999; Roni et al., 2002), we risk losing the diversity of habitats critical to the persistence and diversity of aquatic species (Bisson et al., 1997; Hurley and Jensen, 2001; Poole et al., 2001).

Approaches to ecosystem management that attempt to integrate forest and aquatic goals and incorporate disturbance and recovery processes have been outlined (Reeves et al., 1995; Cissel et al., 1998, 1999; Seymour and Hunter Jr., 1999; Naiman et al., 2000), but implementation has proven difficult. The Interior Columbia River Basin Ecosystem Management Project (Quigley and Arbelbide, 1997; USDA/USDI, 2000), for example, attempted to address the problem of managing disturbances in a more natural way over a very large area, but it was never fully implemented. The inability of management and regulatory agencies, and the public, to articulate common goals and conceptual approaches to land management remains part of the problem. Until there is improved coordination and recognition of a common conceptual framework for management actions, conflicts are likely to continue.

4. Questions for research

Knowing that management decisions will be made without complete information makes it critical to guide research to issues where new knowledge provides rapid help to policy-makers. We strongly recommend that additional research be directed toward the following questions.

4.1. What are the important effects of naturally occurring fires and forest management on aquatic ecosystems, and how can vegetation be managed to better emulate the effects of wildfire?

Natural disturbances, including fire, help create and maintain complex and productive aquatic habitats.

Management projects will occur whether the goal is to restore or mimic natural patterns of vegetation or to provide important goods and services. Making the results of management consistent with natural patterns and processes (e.g. delivery of sediment and wood) that structure aquatic ecosystems will be important goals. Understanding the differences between wild and managed fire and how to mitigate those differences will be key to achieving aquatic conservation goals. This is especially critical in some areas of the western USA, where fuel conditions created over the last century have altered contemporary fire patterns from those that would occur under natural fire regimes.

4.2. How do aquatic habitats vary as a result of fire-related disturbance, and what is the range and distribution of habitat conditions that form appropriate management targets across space and through time?

The dynamic view of landscapes and aquatic ecosystems implies that the conditions of habitats and populations will vary in time and space. To evaluate the status or condition of aquatic ecosystems and the success of management, it will be necessary to consider the distribution of conditions across "populations" of streams (Benda et al., 1998). Knowledge of the variation expected under natural conditions (including changing climate regimes) or conditions necessary to maintain diverse and productive aquatic ecosystems will be required.

4.3. Where are the critical areas for aquatic conservation and restoration, i.e. which places have high priority in terms of ecological value?

Not every population or watershed can be conserved or restored. Some may be more important than others in an ecological or evolutionary sense. An ability to consistently recognize and predict the distribution of important elements of biological diversity or evolutionary potential, and key source areas for the maintenance of populations in dynamic environments will be important to prioritize the limited resources available for conservation management. Ongoing fire and fuels management priorities may be constrained for some time by this context.

4.4. How do we characterize the risks that aquatic communities and sensitive populations face from fire, or fire-related management?

Conservation management is generally prioritized based on ecological value, evolutionary significance, and the risk of loss. Some watersheds and populations are vulnerable to disturbance, the invasion of exotic species, or environmental changes such as climate shifts. In some cases, active management can mitigate those risks; in others it may not be effective. Understanding the nature of those risks will be needed to use limited conservation resources effectively.

4.5. How do we restore ecological processes that are critical to creating and maintaining productive and resilient aquatic ecosystems, and simultaneously restore and maintain productive and resilient terrestrial ecosystems?

There has been much debate about the relative merits of active versus passive ecological restoration (NRC, 1992, 1996). Proponents of active restoration argue that intervention is needed to accelerate the recovery of ecological processes. Proponents of passive restoration argue that damaged ecosystems are capable of self-recovery if major anthropogenic stressors are removed (Beschta et al., 1995; Ebersole et al., 1997). Management options that reduce the probability of uncharacteristically severe fires (especially in areas where fuel conditions reflect decades of fire suppression, such as the lower and mid-elevation forests in California and southwest Oregon and the pine forests of Arizona and New Mexico) will diminish the need for post-fire rehabilitation. For some watersheds that experience high-severity wildfire, some combination of active and passive approaches will be needed; the problem is deciding where, when, and how effective restoration actions can be most efficiently implemented.

4.6. What are the advantages and disadvantages of post-fire rehabilitation, and under what circumstances is such rehabilitation warranted?

Improved methods are needed to evaluate post-fire watershed conditions following severe wildfire (Robichaud et al., 2000), particularly methods that assist in determining the need for immediate restoration actions. Issues of concern include: (1) the likelihood of severe erosion and flooding following large fires; (2) the expected differences in watershed recovery rates and ecological trajectories that will occur under natural recovery or active rehabilitation (i.e. BAER) scenarios; and (3) the economic and ecological costs and benefits of alternative actions. In particular, improved understanding of the natural recovery of aquatic ecosystems in the wake of fires is needed. When, for example, is it important to allow some amount of erosion, debris flows, flooding, and restructuring of channels in the short term as an advantage to aquatic species and habitats in the long term?

5. Addressing uncertainty

Any approach to integrating fire, fuels, and aquatic ecosystem management has inherent risks and uncertainties. In the long term, the most promising paths to managing complex, integrated systems adjust both to changing conditions and new information. The National Fire Plan offers a unique opportunity for learning because it mobilizes research and management towards common goals and promotes integration. Several premises concerning wildland fire, fuel, and aquatic species management follow from the papers included in this issue and our view of the current situation: (1) severe wildland fires will occur throughout the western USA in the coming decades; (2) the management response in most cases will be a mixture of suppression and containment; (3) post-fire treatments of various kinds and intensities are likely in severely burned areas; (4) fuel and thinning treatments will be prescribed to mitigate fire extent and severity; (5) treatments in or near urban–wildland interface areas will initially take precedence; and (6) populations of aquatic organisms often are depressed in the same areas where severe fires are likely and fuels treatments will be targeted.

Despite clear program direction and commitment to action, understanding of the ecological ramifications of wildland fires and our responses to them is limited. Although we understand much of the physics of fire behavior in forest stands under controlled conditions, understanding wildland fire behavior at landscape scales is still evolving. Hence, the efficacy of treatments in affecting the extent and severity of wildland fires is uncertain. Landscapes are changing in ways that are novel to our collective experience. Climate, topography, fire suppression, and post-fire rehabilitation are additional factors clouding our view of the future landscape.

Over the past 25 years, the concept of adaptive management has been introduced in natural resource management (Holling, 1978; Walters, 1986; Lee, 1993). It has the potential of becoming highly influential, but that influence has not yet been realized. The adaptive management model recognizes that management plans are made with imperfect information and understanding, and management decisions often lead to unintended or unsuspected consequences. The central tenet of adaptive management is that, acknowledged or not, management is inherently experimental. In natural resource management, all decisions can be interpreted as hypotheses about how the world works; outcomes of actions potentially provide support to each hypothesis. Adaptive management uses rigorous experimental design, a structured decision process, and monitoring to help distinguish between competing hypotheses.

Despite its strong scientific basis and emphasis on learning, examples of successful application of adaptive management are scarce. Commonly identified barriers can be grouped as primarily social, institutional, ecological, or technical (Walters, 1997; Rogers, 1998; Gunderson, 1999; Lee, 1999; Gray, 2000). Gunderson (1999) notes that adaptive management requires flexibility in the power relationships among stakeholders, as well as resilient ecosystems. Social or institutional barriers often involve stakeholder groups that resist experimentation when they perceive risks to their interests. Growing awareness of the importance of stakeholder involvement has lead to various outgrowths of adaptive management, which emphasize participatory research and decision processes (Bormann et al., 1999; Shindler and Cheek, 1999; Lal et al., 2001; Walker et al., 2002).

In the case of fire, fuels, and aquatic ecosystem management, many potential actions involve competing risks, e.g. the risk of affecting sensitive aquatic species versus the risks to people, property, or other resources from fire. The common approach is to negotiate settlements, location-by-location, through bureaucratic, political, and legal processes. Debates are often highly polarized with each side arguing their position based on a selective use of science. Resolving uncertainties would seem to have great social value. An experimental management approach would be to set up areas with various treatments and evaluate the results. Doing so requires an acceptance of risk, however, it is perceived, for the sake of learning.

The western landscape is not homogeneous with one set of conditions, governed by one agency, with one set of stakeholders. Rather, it is a broad, heterogeneous, and fragmented landscape with tremendous diversity despite some common themes. Management is effected not by a single decision, but by many smaller-scale decisions and actions. Each fuels treatment or response to wildland fire is unique in its ecological circumstances and in its social context. Local decisions are based on a blend of national, regional, and local values. The ad hoc nature of local decision-making hinders establishing a rigorous regional-scale experimental design.

The first step in establishing a successful program of adaptive management for fires, fuels, and aquatic ecosystems in the western USA is to establish reasonable expectations in light of the various barriers to implementation. The best hope for success might be a combination of passive adaptive management across the entire landscape with more directed active adaptive management in targeted areas. In a passive adaptive management approach, land managers monitor the effectiveness of a plan and its actions and make adjustments to the plan based on their observations and new insights. An active adaptive management approach tests alternative management treatments, each based on different assumptions about how ecosystems function and how they will respond to treatment. Both approaches require: (1) well-articulated hypotheses of how ecosystems will behave; (2) commitment to monitoring and rigorous data gathering; (3) creative, yet rigorous analytical approaches to provide inferences based on data. Analytical approaches must facilitate evaluation of the ecological importance of statistically significant observations.

The key difference between the active and passive approaches is that the active approach is based on a more traditional experimental design that seeks to replicate observations and control for the many confounding influences within the context of an operational management program. The active approach is suited to experimental and pilot forests where increasing knowledge about key questions is a primary objective. Expanding the network of experimental sites would provide increased opportunities for testing different active management options. Rigorous experimental designs allow for stronger inferences from fewer data, but have the disadvantage of reduced applicability. One way of increasing applicability is to follow the model proposed by Johnson (1999) of working in small, replicated ecosystems and focusing on a general class of problems that require similar decisions. The idea is to develop general procedures and guidelines that can be broadly applied with local modifications for site-specific differences.

In contrast, passive adaptive management is more observational than experimental. Such studies are common in fields like econometrics where the ability to manipulate the system under study is limited (Spanos, 1999). To provide useful inferences, the passive approach requires an extensive data-collection effort. Many observations are needed to separate signal from noise. For example, Lee et al. (1997) detected management influences on stream channel characteristics in the Columbia River Basin by an analysis of channel inventory data from over 6300 reaches in nearly 2000 streams. Statistical inferences were possible because of the concerted effort by land management agencies to collect and catalog large amounts of data. A similar effort is needed to coordinate data collection and analysis regarding fire and fuels management influences across the western states.

Ultimately, the success of any management strategy will depend on acceptance by the public. Research has consistently shown that genuine public collaboration enhances both the quality and acceptability of agency decisions (Bormann et al., 1999; Hummel and Freet, 1999; Shindler and Cheek, 1999). The National Fire Plan offers a unique opportunity for participatory research, i.e. an integrated approach involving research and management personnel from each of the public and tribal land management agencies, plus principal stakeholders and interest groups. Such an approach can be used whether the management is active or passive. Entirely new associations between managers, researchers, and the public are needed to design, implement, and monitor management. On one hand, scientists can help identify questions, apply rigorous scientific design, and experimental treatments based on management constraints. Managers can implement projects that can be treated as experiments with hypothesized outcomes, adequate controls, and replication. Politicians and interest groups can suspend disbelief and work closely with managers and scientists to identify strongly held values, gauge risks and uncertainties, formulate potent management experiments, and help implement and monitor results.

Uncited references

Bradshaw and Borchers (2000), Long et al. (1998), Taylor et al. (2001), Walters and Holling (1990).

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