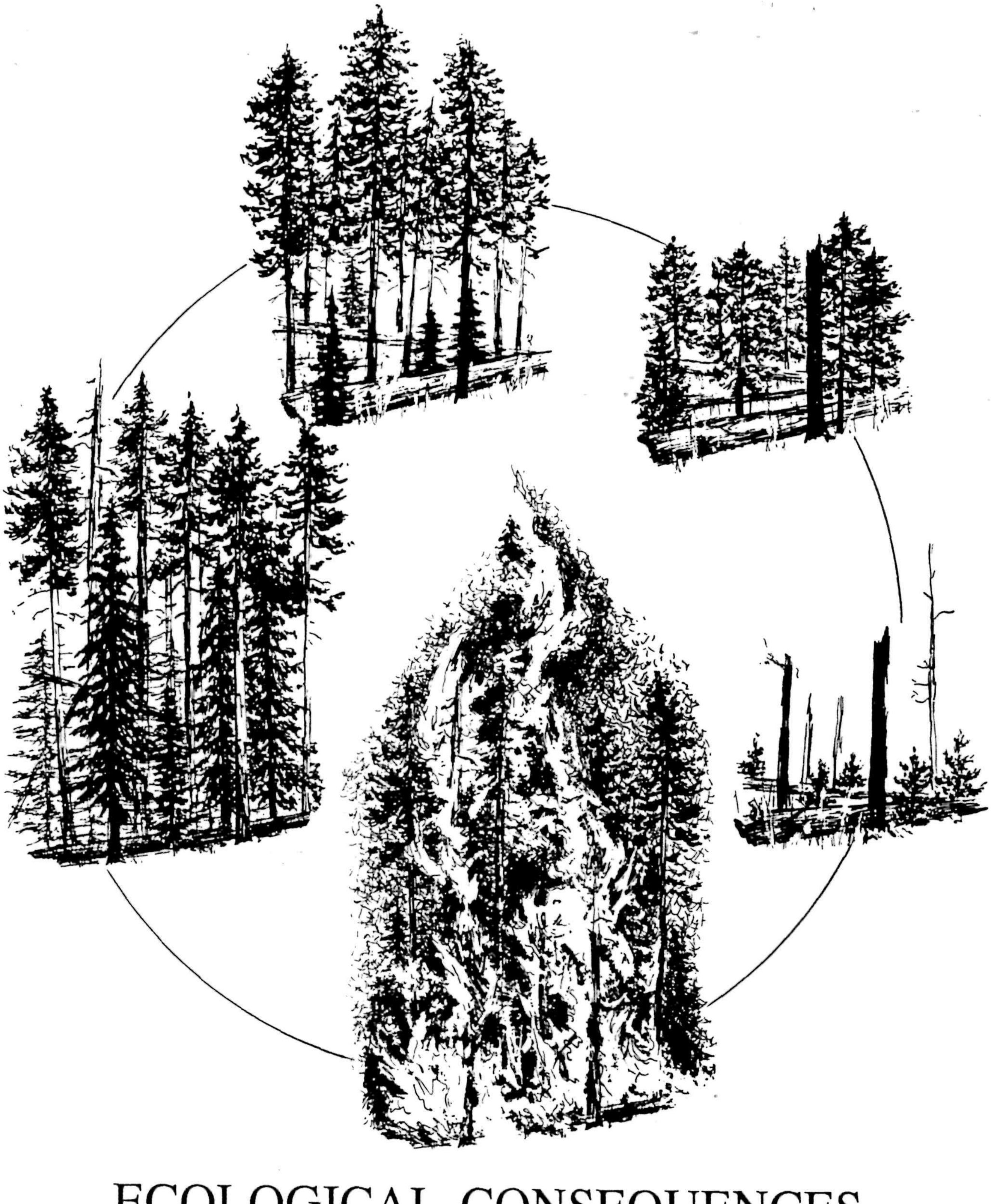

ECOLOGICAL CONSEQUENCES of the 1988 FIRES in the GREATER YELLOWSTONE AREA

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FINAL REPORT

THE GREATER YELLOWSTONE POSTFIRE ECOLOGICAL ASSESSMENT WORKSHOP

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Introduction

The Greater Yellowstone Postfire Ecological Assessment Workshop was held 18-20 November 1988 under the sponsorship of the Greater Yellowstone Coordinating Committee. The charge to workshop participants included six objectives.

1. Evaluate the apparent ecological impacts and implications of the 1988 fires as they relate to the area's watersheds, fisheries, wildlife, forests, soils, ranges and biological diversity.

2. Consider the short- and long-term need for reseeding these areas for soil stabilization and erosion control.

3. Evaluate the need or desirability of a reforestation program in the parks, in wilderness areas, and in public commercial forest stands.

4. In light of both the drought and fires of 1988, consider the need or desirability for supplementary feeding of ungulate species during the winter of 1988-89.

5. Develop a list of short- and long-term postfire research needs.

6. Prepare a report summarizing the workshop proceedings, to include ecological impacts and implications, and any recommendations about alternatives and/or options the agencies may want to consider in future management programs.

An interim report dealing with charges two, three, and four was delivered to the Greater Yellowstone Coordinating Committee on 1 December 1988 (see Appendix A). During December, individual panelists prepared reports on fire effects related to their expertise. These were collated and circulated among panel members prior to a second meeting held 13-14 January in Denver, Colorado.

At this Denver meeting the panel agreed that its final product should accomplish three goals. First, it should provide, in a form accessible to the public, a general report of the 1988 fires, their currently perceived ecological impacts, and their significance with respect to past, current, and potential future management practices. Second, it should include a technical report that provides scientific documentation of the likely ecological consequences of the 1988 fires. The panel was unanimous that this report should emphasize areas of ignorance as well as understanding. Third, using the technical report as a guide, the product should outline research needs and opportunities.

This final report is thus divided into three sections corresponding to these three goals. In the first section we summarize our understanding of the events leading up to the 1988 fires, the ecological consequences of the fires, and recommendations regarding proposed postfire mananagement interventions. In this section we have also attempted to interpret our observations and recommendations in the context of larger issues relevant to wilderness ecosystem management. The second section is a technical review of the state of our understanding of the specific ecological impacts of the 1988 fires. To the extent possible, we have documented the specific short- and long-term ecosystem responses we expect. More important, we have attempted to identify areas of uncertainty and variables that could affect the course of future landscape change. Based on information presented in the previous sections, we outline research needs and opportunities presented by the 1988 fires. Rather than describing specific research projects, we approach these issues in general terms, emphasizing the importance of vigorous and carefully planned monitoring and research defined and driven by the goals of wilderness management programs.

Aside from the initial November workshop and access to data on the 1988 fires, the panel carried out its deliberations independent of involvement with the Greater Yellowstone Coordinating Committee. Nevertheless, we are grateful to Greater Yellowstone Area Agency personnel for timely responses to requests for documents or queries for information.

We recognized early in our deliberations that the 1988 fires in the Greater Yellowstone were a paradigm for major issues in the management of wilderness ecosystems. Only a miniscule portion of once vast wilderness landscapes has been preserved and the boundaries and spatial extent of these preserves bear little relationship to the natural processes necessary for their preservation. The 1988 fires have laid bare the broad extent of our ignorance of those natural processes. It is our sincere hope that this report not only documents these dilemmas but provides meaningful guidance for their resolution.

Respectfully,

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Executive Summary

By October 1988, a complex of fires originating from both lightning and human-caused ignitions had burned 1.41 million acres in the Greater Yellowstone Area (GYA). Of this acreage, 60.6% was burned by canopy fire, 33.7% was burned by surface fire, and the remaining 5.7% was meadow, grassland, or sagebrush. Among the factors contributing to the extent and severity of the fires were successional changes leading to large expanses of flammable old-growth forests on the GYA landscape during the past century, unprecendented drought conditions, and persistent winds. The large-scale behavior and extent of the fires appear to have been established more by drought and wind, although fuel distribution certainly affected fire intensity and behavior on a local scale. The events of 1988 demonstrated that fire suppression in heavy fuels may be impossible when weather is severe.

Although fires of this magnitude are unprecedented on the GYA landscape since establishment of Yellowstone National Park in 1872, fires of similar size have burned elsewhere in western montane ecosystems during this century and also probably occurred on the primeval GYA landscape. There is considerable evidence that a fire of similar proportions burned across the Yellowstone Plateau in the early eighteenth century. Such fires may have occurred at intervals of hundreds of years in association with successional changes in forest fuels and the coincidence of favorable climatic conditions.

From the standpoint of sources of ignition, the 1988 fires cannot be considered entirely natural. However, their behavior and likely ecological consequences are completely within the range of fire effects that has so greatly influenced the evolution of the Yellowstone biota. Rather than ecological disasters or castastrophes, high-intensity fires in ecosystems such as those of the GYA are virtually inevitable, and are even essential for the successful reproduction of some species. The processes that have regulated ecosystems in the GYA for millennia will continue to operate. The complex mosaic created by the 1988 fires will initiate successional processes that will guarantee future landscape variety and diversity.

For wilderness ecosystems, human intervention in these processes are not only unnecessary, but may be detrimental. However, where potential impacts on non-wilderness ecosystems are great, artificial interventions may be required. Nevertheless, interventions that diminish wilderness values should be pursued only if the threat to non-wilderness ecosystems is clear and only if it is certain that such interventions will achieve their intended goals. On these grounds, artificial feeding programs for ungulate mammals, seeding of short-lived alien plants for soil stabilization, or artificial reforestation programs are either unnecessary and inappropriate. Prudence argues against aggressive intervention, but it also argues for continued monitoring and reevaluation of these recommendations.

There are uncertainties regarding many of the specific ecological consequences of the 1988 fires. The course of many future events will depend heavily on factors such as climatic variation which we have only a limited capacity to control or predict. We have much to learn about the interactions between site variables, vegetation, climate, and spatial scale that will produce specific responses to fire. The 1988 fires have created an important opportunity for research on these issues.

A coordinated program of research on the 1988 fires should be intiated immediately. The essential ingredients for such a program include an ecosystem approach to provide conceptual integration and operational coordination of many individual research projects, a landscape approach utilizing geographic information systems, and provision for long-term studies and monitoring of key system features and processes. The Yellowstone fires do not simply provide another place to study the ecological consequences of fire. Rather, their uniqueness lies in their heterogeneity and scale, and in their significance to the future wilderness management.

Part I. Interpreting the Yellowstone Fires of 1988

The fires that burned over the Greater Yellowstone Area during the summer of 1988 were remarkable for their intensity and their scale -- the largest fire complex ever recorded for the Greater Yellowstone Area, the biggest in the Northern Rockies during the last half century, and one of a score of large-scale burns that have dominated the fire history of the United States during the course of the past century. The fires demonstrated with extraordinary power the principles of wildland fire propagation, the conditions under which humans can and cannot intervene with large fires, and the ecological interdependencies that link biotas to large burns.

That the Greater Yellowstone Area (GYA) has enjoyed status as protected land for a century or more -- the site of America's first national park (1872) and its earliest national forest (1891) -- makes the region particularly valuable as an environment for scientific understanding of the role of fire in wildlands. Over the past two decades much of the GYA has been committed to the national wilderness preservation system, and the park itself has been designated as a Biosphere Reserve by the Man and the Biosphere Program of UNESCO. The existence of base-line scientific data on a number Yellowstone landscape features will permit evaluation of the short- and long-term ecological consequences of these fires. Thus, it is possible to view these fires as more than a natural disturbance. They have special scientific significance.

As a cultural phenomenon, the Yellowstone fires are likewise distinctive for the intensity and scale of media attention given them, for the unprecedented costs of their attempted suppression, and for the timely test they have provided of the philosophies, policies, and programs of parks and wilderness areas. The lessons are vital, the outcome is assured of public visibility, and the interpretation of these phenomena is rife with national and even international significance.

It was a century ago that the Federal government inaugurated fire protection on public wildlands, when the U.S. Cavalry assumed administration of Yellowstone National Park in 1886. It was 20 years ago that the National Park Service, building on recommendations coded into the Leopold Report (1963), reformed its management philosophy. In 1968 the Park Service modified its fire policies so that parks could more readily adopt programs of prescribed fire and, where appropriate, incorporate naturally ignited fires into the overall agenda of park management. The Yellowstone fires are a critical test of those programs and those philosophies.

The Fires

Chronology. Twenty lightning-caused fires early in the summer inaugurated the 1988 fire season. Eleven fires expired at small sizes with no human intervention; the rest persisted under the aegis of fire programs aimed at permitting natural fires. Subsequently they were joined by additional fires ignited by lightning and humans. After July 15, no new naturally ignited fires were allowed to burn freely, with the exception of new lightning fires burning adjacent to existing fires. After July 21, all fires were subjected to suppression. The total fire perimeter on that date surrounded about 17,000 acres. Throughout, some form of suppression was attempted for anthropogenic fires. September snows halted major spreading. The fires were not completely extinguished until the snows, low temperatures, and diminished winds of November.

By October, the fires had affected 1.41 million acres (11%) of the Greater Yellowstone Area. Within Yellowstone Park an estimated 989,000 acres (45%) burned. This includes 562,000 acres of crown fire, 367,000 acres of surface fire in forests, and 54,000 acres of wet and dry grasslands (26, 17, and 2.5 % of the park, respectively). Approximately 60% of this total burned from fires that entered the Park from outside or that began from human causes. Failed backfires from attempted suppression increased the overall dimensions of the complex. In fact, some fires that threatened communities adjacent to the Park, such as Cooke City, emanated from backfires.

As the summer progressed, fire behavior was often spectacular. Crown fires predominated and long-range spotting was prolific, even spanning the Grand Canyon of the Yellowstone River. At its extremes the rate of forward spread reached two miles per hour, an extraordinary velocity for a fire in forest fuels. The growth of fire perimeter and area increased geometrically.

Comparisons and Context. When considered on a regional basis, the 1988 fires followed a classic scenario--regional drought, a rash of ignitions from dry lightning storms and human sources, a steady increase in size and intensity through July, a near firestorm climax in late August. From a historical perspective, fires in fuels such as those that typify much of the Greater Yellowstone Area tend to be either small or very large. Throughout the Northern Rockies a few fires and a few years account for most of the burned acreage. Very large fire complexes have burned under climatic conditions less severe than those experienced in the GYA during 1988, and portions of the Northern Rockies that suffered similar conditions in 1988 escaped with far less burning. In 1910, some 3.25 million acres north of the GYA burned according to a chronology that was remarkably similar to that observed in 1988.

The Yellowstone Plateau displays some special features that influence fire distribution and fire behavior. The plateau itself is an anomalous terrain feature that allows winds to sweep across large expanses of nearly unbroken forest. Conversely, its forests appear to lack the flammable understory that carries fires in many otherwise similar sites. As preposterous as it may now seem, the experience with natural fire during the prior 16 years of the natural prescribed fire program indicated that the Yellowstone landscape was comparatively nonflammable. During this period, 235 fires had burned only 34,157 acres in the GYA; the largest single burn was 7,400 acres. The average size of natural-ignition prescribed fires during this period was 250 acres and most burned out on their own long before reaching that dimension. Limited forest and historical data indicated that large fires followed the cycle of forest maturation, that fuel conditions confined large fires to old lodgepole pine or aging spruce-fire forests. Within these very long cycles -- on the order of two to three centuries -- outbreaks of large-scale fire probably coincided with episodic droughts. The fire plans under which natural fire programs were administered in the GYA accepted these precepts. Past experience supported the assumption that the sheer size of the wilderness area would be adequate to accommodate any fires that might occur.

The large-scale behavior and extent of the 1988 fires appear to have been established more by drought and wind than by fuels. Virtually all categories of forest age and fuels burned. Although precipitation was above normal in May and April, there were dramatic deficits in June (~20% of normal), July (~79%), and August (~10%), and 1988 ended as the driest year on record. The summer drought, moreover, followed several years of low average annual precipitation. These dry conditions may have made flammable fuels that in normal years were too wet to burn. Limited fuel moisture data prevent conclusive statements in this regard. The second critical element was the wind regime. Winds drove flames into and through the crowns, where the greatest concentrations of fine fuels existed. The size of the fires assured that they could not be stopped by small changes in microclimate, landforms or fuelbeds, or by fireline suppression. Nevertheless, these factors did influence fire behavior on small spatial scales and contributed significantly to the resulting mosaic of burn intensities.

How "Natural?" The 1988 fires did not burn untrammeled by human actions. Human-caused ignitions were responsible for fires in well over half of the burned area. Perhaps lightning strikes would have set fire to some of these areas anyway, but there can be no doubt that human-caused ignitions altered the extent and pattern of fire that would have occurred in their absence. Fire suppression did not extinguish any of the large fires, but may have introduced additional fire in the form of backfires. And, it is argued by some, a century of fire suppression greatly increased the total size of the 1988 complex because of fuel accumulation.

This last proposition is difficult to prove with any rigor. Fire suppression was the policy at Yellowstone Park and adjacent national forests for most of their history. Attempts to enforce this policy began after the U.S. Cavalry assumed responsibility for park administration in 1886. The success of suppression activities probably varied among ecosystems (e.g., grasslands versus forests) and with changes in fire-fighting technologies. The development of airborne fire-fighting technologies in the 1930s and 1940s undoubtedly increased the ability to suppress fires, but to what extent is a matter of debate. Although difficult to quantify, historical changes in patterns of landscape use have certainly altered fire regimes in the GYA. Prior to 1900, Native Americans may have provided important ignition sources by broadcast burning range areas or from escaped campfires and signal fires in forested areas. Patterns of use and fire suppression in landscapes adjacent to the GYA probably have influenced fire regimes also.

In the sense that these fires were influenced by past and present human activities, they cannot be considered entirely natural. However, naturalness in this sense is no longer a realistic wilderness management goal. Given the long tenure of Native Americans in this region and their potential, albeit unknown, impact on fire regimes, whether naturalness so defined is even a desirable wilderness objective is a subject open to legitimate debate. The acceptability of events such as the 1988 fires in the context of a wilderness preserve should be judged less on the basis of their causes than their consequences.

Ecological Considerations

The fires burned under assorted conditions. Fuels, winds, and terrain varied, resulting in heterogeneous patterns of burning will lead to heterogeneous responses from the biota. Some of these responses will follow known precedents. Some, however, must be considered unique.

Large Fires and History. Although infrequent, large fires are typical for the region. Substantial areas of forest on the Yellowstone Plateau, for example, apparently date from fires that burned several hundred thousand acres in the early 18th century. Whether such fires ever approached the scale of the 1988 events is not known. Because crown fires are integral to the dynamics of the Yellowstone landscape, it is impossible to exclude such fires from these ecosystems and still retain its natural character. For example, the interdependence of crown fires and the growth and reproduction patterns of lodgepole pine has been well documented. Some species (such as aspen) that were steadily declining in vigor, may be rejuvenated. The fires will shift species composition but not drive any to extinction. However, establishment opportunities for aggressive alien weeds could occur.

Most of our understanding of ecosystem responses to fire is based on studies of events of considerably smaller scale. It is unlikely that the large-scale consequences of the 1988 fires can be predicted by simple extrapolation of our small-scale experiences. The impact of scale is not well understood. This fact alone should make us suspicious of unequivocal predictions.

The history of the Yellowstone landscape is not merely one of cycles, endlessly repeated. The 1988 fire complex will not simply rejuvenate the Yellowstone of the past, but will, using the existing biotic materials, re-shape its ecological future. The conditions that created the Yellowstone encompassed by the 1872 legislation no longer exist exactly. There have been subtle changes in climate. The park and surrounding wilderness areas are not isolated from events that have occurred around them. There is a legacy of chance occurrences that is now encoded in the composition and dynamics of Yellowstone's landscape. That past cannot be replicated exactly, nor can it be erased.

Proposed Interventions. There are compelling arguments for a light hand in coping with the unique scene created by the fires of 1988. The ecological processes that have regulated Yellowstone landscapes for millennia will continue to operate, though in different proportions, on different scales, and at different rates. The Yellowstone that emerges from the 1988 fires will strongly resemble the Yellowstone that predated them, its differences ones of emphasis. These changes will require monitoring, but emergency intervention in the Park does not appear to be necessary. Artificial feeding of ungulates (elk, deer, etc.), seeding with short-lived alien herbs in areas subject to erosion, and artificial reforestation activities to speed ecosystem succession are among the interventions thus far proposed by some groups.

The borders of wilderness preserves have for the most part been defined on the basis of political and economic criteria, with little or no regard for natural divides or ecological boundaries that regulate natural processes. The consequences are reciprocal: an event outside wilderness preserves can affect ecosystems within, and events within wilderness ecosystems can reach outside the preserves. Where the potential impacts on non-wilderness ecosystems are great, artificial interventions may be required. Nevertheless, interventions that diminish wilderness values should be pursued only if a threat to non-wilderness ecosystems is clear, and only if it is reasonably certain that such interventions will achieve their intended goals.

Feeding. Artificial feeding programs are expensive, alter animal behavior, facilitate spread of disease, and usually do not work. Programs such as these focus attention on single components of ecosystems, especially the "charismatic megafauna" (e.g., bison, elk, bears, etc.), and reflect an unwillingness to accept the fact that natural processes in wilderness ecosystems often have results that in human terms appear to be cruel. Wilderness preserves should not be managed as either zoos or museums, item by item. Rather, the goal is to preserve the complexity of dynamic interactions among the various ecosystem components that are essential to its functioning.

Soil Stabilization. The erosion processes that shape wilderness landscapes do not operate at constant rates, but rather occur in episodes often associated with natural disturbances such as fire. The 1988 fires probably will alter runoff and increase erosion in many locations on the Yellowstone landscape. Within the context of wilderness, such changes are expected and in some cases even desirable. The geomorphologic and hydrologic consequences of the Yellowstone fires certainly are legitimate concerns for non-wilderness ecosystems downstream. However, the potential impacts currently do not appear to be sufficient to warrant an emergency soil stabilization program, particularly given the risks to wilderness ecosystems. Remedial measures such as seeding with alien species may temporarily stabilize soils, but in the long term they can actually accelerate surface erosion by interfering with establishment of native plants and encouraging their replacement with noxious weeds. Nevertheless, our ignorance of the complexity of these interactions argues for careful monitoring and reassessment of needs for seeding on burns.

Reforestation. Other proposed remediations, notably artifical reforestation, should be evaluated according to whether the lands are wilderness or not. In acknowledging fire as an integral process of natural ecosystems, we must also accept the natural processes of postfire ecosystem change as an integral part of wilderness landscapes. Nearly all native species in these ecosystems are adapted to or depend on fire in one way or another. What specific patterns emerge will depend on such factors as prefire ecosystem structure and species composition, specific site environments, local patterns of fire severity, and unpredictable postfire events including year-to-year variations in climate. In ways we are just beginning to fathom, it was this combination of variables that was responsible for much of the variety of the Yellowstone landscape prior to the 1988 fires and that will undoubtedly contribute to the heterogeneity of that landscape in the future. It would be difficult, if not impossible, to devise a reforestation strategy that could replicate this marvelous diversity. Furthermore, artificial planting would likely alter the distribution of tree genotypes. However, in lands dedicated to commercial forestry or adjacent to human developments, there may be a case for reforestation activities.

Intervention and Ignorance. The technical portion of this report suggests considerable uncertainty regarding the specific ecological changes to be expected as a consequence of the 1988 fires. A portion of this uncertainty can be resolved with a vigorous, carefully planned program of research and monitoring. The 1988 fires present important and unequaled opportunities for such programs. Nevertheless, a substantial portion of this uncertainty is a consequence of the innate unpredictablity of certain future events such as annual and long-term climate changes. Thus, even as our knowledge base increases, some level of uncertainty is inescapable.

If prudence argues against aggressive intervention, it also argues against a doctrinaire strategy of laissez-faire. It would be reckless and irresponsible to commit irrevocably all of the Yellowstone biota to a purely "natural" succession of events when the scale of the disturbance involves half the wilderness and the future pathways of landscape change are known only within broad parameters. If our state of knowledge argues against emergency intervention, our state of ignorance argues for a program of aggressive data collection and evaluation. A monitoring network adequate to gauge postfire changes simply must be present in order to compare actual developments with forecasts and thereby make informed judgments. In order to thrive, that monitoring program must complement an active agenda of scientific research.

Cultural Considerations

The Yellowstone fires burned within a cultural no less than an ecological context. Smoke and flame temporarily upset local economies based on tourism. These will recover--the fires became "prime theatre" and it is likely that the great burns will themselves become prized objectives of future tourists. Off-site effects will also include water and wildlife, though specific consequences for surrounding settlements are not known.

Parks are administered within a matrix of legislative mandates, agency directives and policies, and locally prescribed policies and protocol. Elements of this matrix both proscribe and prescribe certain actions, but do not dictate a single, monolithic scheme at all parks. Management ambiguities almost necessarily result. The National Park Service Act, for example, enjoins the Service "to conserve the scenery and the natural and historic objects and the wild life therein and provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations." This is an ambivalent, if not outright contradictory, charge. Fire management programs do not follow as a syllogism from national policies and handbooks. The need to allow for local discretion and to accommodate local situations perpetuates rather than removes these ambiguities and uncertainties. Yet, too often guidelines assume knowledge where there is ignorance. Policies assume consensus where there is conflict. Programs presume an exact harmony where a working approximation is normal.

Fire exacerbates these ambiguities. Humans have a special relationship with fire that makes it different from other natural eruptions of energy such as earthquakes or tornadoes. That humans have directly or indirectly manipulated fire for some 1.5 million years, that the biotas of North America have experienced anthropogenic fire since the recession of the last glaciation, complicates enormously decisions about what fire practices are appropriate to a particular place and time. Fires on the scale of those in Yellowstone demand decisions, but also distort and magnify inevitable flaws in protocols for making such decisions. When fires of this magnitude occur in a place that can attract major media attention as can Yellowstone, they take on the character of a celebrity scandal.

Fire Management Considerations

Americans have not set aside wilderness areas and parks in order to manage fire. They apply and withhold fire to serve the objectives for which they have reserved those lands. Ecosystems cannot be designed solely to reduce fuels, suppress wildfire, or to encourage naturally-ignited burning. But the founding ambitions for many natural preserves are often ambiguous and sometimes at cross-purposes; it is not obvious how to manipulate fire to advance their objectives. Equally, fire brings its own demands. Fire is not a biotic probe, a precision caliper by which to improve habitat for elk or to regulate the age structure of lodgepole pine. Fire is not only an anthropogenic tool but an ecological process in its own right. Moreover, humans have a special relationship with fire no less than that they enjoy with charismatic species like elk, moose, or bison.

Strategies of Fire Management. Humans can intervene with fire in ways that they cannot intervene with volcanoes or hurricanes. Often we can apply or withdraw ignition, and we can reshape the environment within which a fire may burn. Both fire suppression and prescription, however, pivot on a paradox. The only way to eliminate wildland fire is to eliminate wildlands. To extirpate fire completely from a wildland ecosystem is to remove an essential component of that wilderness. Similarly, to alter the fuels in a significant way is to change the character of the wildlands that are being protected. The strategy has thus evolved to substitute various kinds of controlled or prescribed fire for wildfire. Designating naturally ignited fires as prescribed fires or as "confined" suppression fires belongs within this spectrum of management options.

What makes the situation compelling is that there is no truly neutral position possible. Fire suppression does not quick-freeze an ecosystem, which changes by having fire withheld as surely as it changes by being burned. Controlled burning assures a presence for fire, but the choice of fire intensity, size, and burning schedule inevitably selects for some species over others. Allowing only lightning-caused fires to burn will not necessarily restore or replicate the fire regimes that shaped a primeval wilderness. Such a strategy may not account for landscape changes adjacent to the preserve, and it assumes that burning by native peoples was unimportant or irrelevant to management objectives. Furthermore, where preserves have been established to protect certain species, there is no assurance that these species will survive under a such a fire regimen. Even the failure to choose among fire management strategies becomes itself a choice.

No single approach to fire management is complete in itself. Each is vulnerable to arson; each breaks down when confronted with exceptional conditions that lead to complexes of large fires; each suffers operational failures. It is not possible to prevent all fires, especially where lightning is a prolific source of ignition. Similarly, controlled burns can escape. Wildfires rage even in areas that bristle with high-technology fire suppression forces. Each approach brings its own environmental liabilities. No strategy is inherently right or wrong, but only becomes true according to the capacity of the receiving environment to accommodate it and of agencies charged with management of wilderness ecosystems to express it in operational terms.

Policies and Management Plans. Fire management on public lands now operates under a pluralistic policy that allows in principle for an equilibrium between fire use and fire control. Within the decision to suppress a fire, a number of responses are possible. The Yellowstone fires do not so much challenge the wisdom of that policy as they do the support necessary to implement it. Fire management plans must include, in the context of detailed written presciptions, guidelines for monitoring and evaluating natural prescribed fires. Presuppression plans to guide major fire control operations are essential. Care must be taken that interagency agreements to harmonize procedures for accepting fires along administrative borders do not disguise very different operational criteria for distinguishing between prescribed and wildfires. The acceptability of naturally ignited fires must be conditioned by the contraints of preserve design and size. Fires that might be considered "natural" by various criteria will not necessarily be acceptable in the context of such constraints.

It is clear that the assortment of fire management plans in the GYA was inadequate for the 1988 fires. It is unlikely, however, that *any* fire plan could have foreseen an event of this magnitude or coped with a complex of fires that, by the time the decision to suppress was made, was uncontrollable. Once a fire becomes large, suppression is often possible only with major changes in weather. A policy of fire by prescription, which is what the GYA plans were, attempts to substitute information for intervention. The GYA plans and programs were based in large part on observations and experience with fire behavior over the past several decades. Clearly, any such information base must encompass larger spans of time.

Wilderness Fire Management

When, following the Leopold Report (1963) and Wilderness Act (1964), the dilemma of fire protection in wilderness and parks became an object of intense scrutiny, many observers believed that wilderness fire management involved merely the restoration of a natural process into a natural environment. The required means were conceptual conviction and political will. In its purest expression, a wilderness fire program sought to withdraw suppression practices and permit naturally-ignited fires to burn freely. Since then the philosophical issues have blurred, and the operational problems have multiplied. It is not enough to withdraw aggressive suppression from wild areas; rather, fire management must blend various forms of suppression with various forms of prescribed fire. A full-service fire program requires information, money, expertise, and commitment. It also must function in the face of considerable uncertainties.

Fire programs must necessarily be predicated on a state of knowledge that is fallible and a capacity for environmental control that is imperfect. It is inevitable that, at some times, the mechanisms will fail. Where a new concept such as accommodating free-burning fire in wilderness is introduced, programs must operate with greater ranges of uncertainties and with few precedents. Many prescribed fire programs were accepted under the assumption that knowledge was adequate to the task of prediction and control. In many places, this is untrue. They also assumed that suppression technologies were adequate to control, almost at will, any escaped fire. This also is untrue. It is unwise for fire agencies to claim perfect knowledge, and it is unfair for the public to demand it of them. Fire plans should be appropriate to the level of knowledge and not attempt to substitute belief or desire for ignorance. Such programs should admit to inherent uncertainties and limitations, and should proceed with a good faith effort. It is not necessary that all specific outcomes of natural prescribed fire programs be known in advance, only that a program be able to specify an acceptable range of outcomes and identify the means by which fire can achieve them.

Critical Components. With regard to wilderness fire, there are two interdependent decisions to be made. First, what kind of fire should be applied? The options are to accept naturally-ignited fire, or to intervene with planned-ignition prescribed burns according to some reasonable schedule, or to accept fires of any origin so long as they burn in specified areas according to some prescribed conditions. There are arguments for each strategy and working examples of each. What cannot be avoided is the need to decide, in advance, how and in what forms fire will re-enter that ecosystem.

If natural-ignition fires are incorporated into plans, a second decision must be made with regard to the scale of acceptable fire. Most biotas show a mosaic pattern of past burning, but the nature of "patches" in such landscape mosaics can vary considerably among different environments. In ways not completely understood, the size of patches affects both the composition and dynamics of ecosystems. The choice of a patch size is a vital decision that will ripple throughout and beyond the site. There may be processes and patterns regulated by large fires that cannot be replicated by aggregating the sum of many small fires. As the Yellowstone fires demonstrate, very large fire complexes can override the mosaic created by smaller fires over several centuries. If such complexes are critical to wilderness landscape processes, we must accept large fires or find some means to simulate the effects attributable to their scale, intensity, timing, and other attributes.

Provided that a site's geography can contain large fires, this argues for a natural-ignition prescribed fire program. Such programs, however, must address two complementary considerations. First, if managers do not monitor and evaluate natural ignitions according to a regular procedure or against specified criteria, then fires are not truly "prescribed." Second, it may be unrealistic to build into plans some threshold for shutting down naturally occurring fires before they can become large. To the extent that this can be accomplished, it may exclude an important features of large or intense fires from the landscape. In any case, it is often technically impossible to terminate a fire simply because it crosses some size or intensity threshold.

Concepts of Preservation. Although as a management tool and a natural process, wildland fire is special. The Yellowstone fires, however, do illuminate more fundamental questions about the precepts and practices by which parks administer natural areas under their care. Increasingly, administrators have emphasized the preservation of natural process rather than simply the preservation alone of natural features, objects, or scenes. Increasingly, they have recognized the subversive consequences of halting natural succession, the futility of recreating a former scene over large areas, the impossibility of translating ideals that have their origins in myth and belief onto natural ecosystems. Even if knowledge of former circumstances was perfect, which it is not, social, climatic, and environmental conditions have so changed that an ideal replication is unlikely. The landscape embodies chance as well as mechanism; and there are those who would argue that chance is itself a value, that the unpredictable is the essence of the wilderness experience.

For two decades the National Park Service has struggled to translate the ideals of the Leopold Report into policies and programs. It was sufficient in the beginning to assert the values of wilderness and to urge parks to envision themselves as wilderness sites as well as pleasuring grounds for the people. The Leopold Report's call for "active management" found selective expression. The critical problems seemed to involve the removal of unwarranted intrusions--the killing of "surplus" elk, the landscaping of scenic corridors, the erecting of structures to transport and house tourists, the suppressing of lightning fire. Instead of the protection of objects, policy substituted the protection of natural processes. Preservation of these processes would lead to the best conceivable outcome.

Our knowledge of the causes and consequences of natural processes such as fire is rudimentary, but we have learned enough to know that wilderness landscapes are not predestined to achieve some particular structure or configuration if we simply remove human influences. . During the past ten millennia the Yellowstone landscape has seen enormous change; indeed, it has probably never looked the same twice. That large or severe fires have occurred in the past is no more compelling justification for including such fires in future management plans than centuries-long fire-free intervals justify a century of active fire suppression. A great variety of future "natural" landscape configurations is possible, although all configurations are not equally likely nor equally desirable. Given the restricted size and arbitrarily defined boundaries of most wilderness preserves, some possible configurations may be far less desirable than others. We cannot escape the need to articulate clearly the range of landscape configurations that is acceptable within the constraints of the design and intent of particular wilderness preserves.

Conclusion

It was easy to promulgate objectives to protect and preserve a particular scene. Developing analogous objectives to preserve and protect particular natural processes has proven considerably more difficult. It is clear that, just as human presence in and around wilderness landscapes is inescapable, human intervention and manipulation will be necessary to preserve those processes. The questions that the next generation of wilderness managers must address are not whether manipulation is desirable, but what kind of manipulation is acceptable? by what means? for what purposes? on what scale? according to what social and political processes? They must rewrite ideals into management objectives, and develop and install monitoring procedures adequate to measure progress towards those objectives. Most important, they must actively support research programs that reduce the state of uncertainty regarding the natural phenomena they are charged with managing. While accepting that that chance exists in the natural world and that management is required even when knowledge is incomplete, managers must also recognize that it *is* possible to narrow the choice of purposes, to contract the range of ambiguity surrounding objectives, and to shrink the domain of ignorance. Many unknowns can be reduced to uncertainties, and uncertainties to probabilities.

The administration of wilderness preserves is complex and formidable, but it is not intractable. The concept of wilderness parks had its origin in the American experience; and the means by which to manage those lands likewise have roots in American culture. In science there is a source of knowledge and measurement, a mechanism for reducing some of the uncertainties that cloud particularly long-term commitments and for addressing those aspects of wilderness management that concern technical intervention. In American pragmatism there exists a formal philosophy to ensure action amid doubt, a working prescription for how to live in a contingent universe about which we have imperfect knowledge. And in the American political process, there exists a medium for expressing public values and for achieving social consensus even on matters for which there are wide opinions and varied beliefs. By these cultural processes the natural processes that form the American wilderness can be preserved and shaped, and the American wilderness can continue to inform and valorize modern civilizations.

Part II. Ecological Consequences of the 1988 Fires

Ecosystems and Landscapes

Like the landscapes we wish to preserve, our understanding of the ecological processes that maintain wilderness has undergone considerable change during the past century. Legislative mandates and management protocols for wilderness parks up to the time of the Leopold Report (1963) were formulated on the assumption that natural successional processes lead deterministically and inexorably to stable, uniform climax ecosystems that are maintained by disturbances such as tree fall that occur on spatial scales much smaller than the size of preserves (Christensen 1988). The structure and dynamics of such climax communities was thought to be a consequence of the "biotic reactions" of a few dominant species (Clements 1916). In the absence of human intervention, it was assumed that wilderness landscapes are predestined to assume a particular primeval configuration determined by relatively static environmental factors such as climate. These ecological precepts were consistent with management goals that focused on the preservation of particular community types and states, or management for specific objects or species. The extent of wilderness preserves was defined to include all of the objects of preservation, and wilderness park boundaries were based largely on political and economic criteria.

It is now accepted that the process of ecological change is far more complex than originally envisioned. Chance conditions soon after disturbance are now known to play a very important role in the process of successional change and to contribute considerably to the natural heterogeneity that typifies most wilderness landscapes (Sousa 1984). Natural disturbances occurring on very large spatial scales were a prominent feature of many primeval landscapes. Furthermore, such disturbances appear to be necessary for long-term preservation of some ecosystem components. As important, it is now clear that ecosystem change does not occur against a backdrop of constant climate; the climatic conditions of today are likely different from those of a century or a millennium ago.

The development of the ecosystem concept has had a marked impact on approaches to wilderness management. Ecosystems are not defined so much by the *objects* they contain as by the *processes*, energy flow and material cycling, that regulate them. Fire is clearly an integral part of these processes in many ecosystems. It is futile to attempt to preserve the structural features of ecosystems without perpetuating the processes that maintain them. Ecologists operationally define the boundaries of ecosystems so as to most easily measure inputs and outputs of energy and matter. It could be argued that the boundaries of wilderness ecosystems should be defined so as to most easily regulate or minimize inputs from and outputs to nonwilderness ecosystems. However, such criteria have rarely, if ever, been used to delineate the boundaries of wilderness parks.

Ecologists have devoted considerable recent attention to the relationships between the spatial configuration and structure of landscapes and the characteristics of ecosystem processes (Forman and Godron 1986, Franklin and Forman 1987). The behavior and spatial patterning of fire and other natural disturbance processes are clearly influenced by the distribution of forest patches of varying successional stage as well as other landscape features. Fire just as clearly affects the future configuration of such features (Knight 1987).

The patch-dynamic model of landscapes (Pickett and White 1985) posits that each patch is constantly changing. If patch size is small relative to the total size of the landscape and if region-wide disturbance frequency remains constant through time, the relative abundance of patches in different successional stage classes should remain constant across the landscape. However, if patch sizes are highly variable and occasionally large relative to the size to the landscape, or if the rate of patch formation changes through time as a consequence of climatic shifts, then the frequency distribution of patch types on the landscape will not be constant through time. We do not know in specific terms how the GYA landscape mosaic has changed during the past several millennia, but available data suggest that the frequency of patch types may have shifted considerably during the past few hundred years in the GYA (Knight 1987, Romme and Despain 1988). It is possible that disturbances such as fire have occurred across this landscape with some regularity. However, the specific pattern of forest patches has probably never looked the same twice. It follows that, if natural disturbances are allowed to occur as they did in the past, the landscape is *not* predestined to achieve some particular configuration. Within the realm of what is natural, a great number of configurations is possible.

Prefire Status and History of the Greater Yellowstone Area

The 11.7 million acre Greater Yellowstone Area (GYA) is composed of parts of the Beaverhead, Gallatin, Custer, Shoshone, Bridger-Teton, and Targhee National Forests and the Grand Teton and Yellowstone National Parks. Approximately 53% of National Forest lands are designated as wilderness, recommended wilderness, and wilderness study areas, with the remainder classified for "multiple use" including commercial forestry. Within Yellowstone and Grand Teton National Parks, well over 90% of the land is classified as "Natural Zone," meaning that "conservation of natural resources and processes is emphasized" (GYCC 1987). Much of this natural zone has been recommended to Congress for wilderness designation.

Nearly all of the GYA lies above 1,800 m (6,000 ft) elevation. Although rugged mountains such as the Absaroka Range, Gallatin Range, and Grand Tetons are prominent features, the more subdued terrain of the Yellowstone Plateau comprises the majority of the GYA and nearly all of Yellowstone National Park. Most of the 1988 fires burned across this plateau.

Forest ecosystems dominated by lodgepole pine (*Pinus contorta*) cover much of the GYA landscape. These forests are most common at 2,300-2,560 m (7,600-8,400 ft) elevation and on nutrient-poor soils derived from rhyolite. Douglas-fir (*Pseudotsuga menziesii*) forests are most abundant at lower elevations (1,800-2,300 m) in the northern third of the GYA. Prior to the 1988 fires, the vast majority of lodgepole pine and Douglas-fir stands in the GYA were classified as mature (100-300 yr since the last crown fire) or over-mature (300+ years post fire) (GYCC 1987). Sagebrush (*Artemisia tridentata*)-grassland occurs in the northern GYA at elevations of 1,500-2,130 m (5,000-7,000 ft). Although the spatial extent of this so-called Northern Range is limited, it comprises a major portion of the winter range for ungulates. At elevations between 8,400 and 10,000 feet, forests dominated by Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*) predominate. Whitebark pine is especially common at higher elevations and is an important food resource for the grizzly bear (Picton 1978). Groves of aspen (*Populus tremuloides*) occur in some recently disturbed areas, as well as at forest grassland boundaries, and on floodplains. Alpine tundra vegetation dominates landscapes above 3,000 m (10,000 ft).

There is no question that fire has played a significant role in all GYA ecosystems (except perhaps alpine tundra) since the retreat of the glaciers 12,000 years ago. Before the advent of humans on this landscape, lightning was the primary source of ignition. Native Americans probably supplemented lightning as a source of ignition over the past two millenia (Pyne 1982), although little is known regarding their specific effects in the GYA. Fire return intervals (the average period of time between successive fires at a particular location) undoubtedly varied considerably since glaciation, within and among ecosytems. Studies by Houston (1973) indicate that fires typically revisited grassland, shrub, and savanna ecosystems of the Northern Range every 20-100 years. However, return times of 200-400 years appear to be more typical of the forest ecosystems that dominate most of the GYA (Romme 1982). The spatial extent of prehistoric fires undoubtedly was highly variable and influenced by weather conditions and landscape features such as topography and distribution of lakes and larger streams. Patterns of past disturbance (including fires and insect outbreaks) also influence fire spread. For example, early successional stands of lodgepole pine established following a fire are relatively nonflammable and may present an effective barrier to fire movement, except during extremely dry years (Romme and Despain 1988). Mature stands with fuel ladders of young spruce and fir trees as well as large quantities of dead fuel are highly flammable (Brown 1975, Knight 1987). Although most prehistoric fires were probably only a few hundred or thousand acres in extent, occasional fires approaching the spatial scale of those in 1988 occurred in the GYA in the early 1700s and before (Romme and Despain 1988).

The impacts of Europeans on GYA fire regimes are complex. In general, commercial and recreational landuse in this region has increased the frequency of ignition events. Nevertheless, fire suppression activities have probably altered the timing, magnitude, and spatial patterns of fires over the GYA. Suppression of wildfires, whatever their origin, was a central feature of military, Forest Service, and National Park Service policy from 1886 to 1972. It is difficult to know the effectiveness of those activities and, therefore, the extent to which fires were actually suppressed because the inaccessibility of much of the wilderness may have hampered enforcement of this policy until the availability of airborne firefighting methods (ca. 1940). However, many fires begin slowly and burn for 6-9 weeks. Thus, hand crews arriving at a fire two or three days following ignition may have been able to suppress a fire unless fire weather was severe or extreme. Fire suppression since the turn of the century almost certainly reduced fire return intervals in accessible light-fuel ecosystems such as the grasslands, shrublands, and savannas of the northern range.

The Fires of 1988

Twenty lightning-caused fires began in June, 1988, but by the end of that month, eleven of these fires had "burned themselves out." Fuel moisture conditions during the spring and early summer appear not to have been abnormally low and the behavior of these fires was deemed to be similar to those that burned in previous years under the aegis of the Park's natural prescribed fire program. By mid-July, Drought had reduced fuel moisture contents to very low levels. Dry fuels and high winds associated with dry Arctic fronts favored rapid spread of the surviving natural fires. By July 15, 3,580 hectares had burned. At that point the decision was made that no new natural fires would be allowed to burn. In other words, *all new* fires would be classified as wildfires and suppression activities would be initiated against them. However, existing natural fires were allowed to burn as were natural fires started adjacent to existing fires. By 21 July, fires had consumed about 7,100 hectares. At this time *all* fires were classified as wildfires and subjected to full suppression. Throughout this period attempts were made to suppress all human-caused fires.

Five of the largest fires (North Fork Fire, Hellroaring, Storm Creek, Huck, and Mink), accounting for over half of the total burn in the GYA, were ignited outside Yellowstone National Park. Three of these were human caused (including the extensive North Fork Fire) and were subject to immediate suppression efforts. Fire behavior in August and September did not vary with ignition source or fire management plan. Suppression efforts certainly were important in protecting life and property, and may have flanked fires in some instances. In most cases, however, fires were gradually extinguished only when weather conditions permitted.

As of December 1988, it was calculated that a total of 0.57 million hectares (1.41 million acres) were actually burned in the GYA; 68% of the burned area is in Yellowstone National Park (GYPRAC 1988). These calculations take into account large areas (>50 hectares), but not small areas, that were left unburned within the overall perimeters of wildfires. Of this acreage, 60.6% was burned by canopy fire, 33.7% was burned by surface fire, and the remainder (5.7%) was meadow, grassland, or sage. These percentages were remarkably constant among administrative units and major fires.

The heterogeneous behavior of these fires was striking. The complex mosaic of burned and unburned areas on spatial scales of hundreds of meters and kilometers will be a dominant feature of the Yellowstone landscape for years to come. Within burned areas, local variations in fire behavior have created great habitat variation which undoubtedly will affect patterns of forest regeneration.

As dictated by management plans, the suppression activities and their impact on the landscape varied between National Forest and National Park lands. A total of 32 miles of buldozer line was cut in the Park, with an additional 105 miles of "catline" in National Forest Wilderness areas. In nearly all areas extensive hand-cut fire lines were made. Localized impacts such as helipads, and fuel and fire retardant spills probably occurred throughout the GYA burned area, but the extent of such impacts has not been assessed to date.

The fires of 1988 demonstrated that, regardless of manpower and equipment, suppression of fires in heavy fuels may be impossible when the weather is severe. The large expanses of old-growth forests on the Yellowstone Plateau (33% of the park was vegetated by stands greater than 250 years old [D. Despain, pers. comm.]) certainly exacerbated this situation. Romme and Despain (1988) found that nearly 20% of a 1,300 km^2 study area in Yellowstone National Park burned in a single fire in the early 1700s. Thus, although the 1988 fires cannot be considered wholly natural, their severity and magnitude may not have been unique in the long-term. However, our current understanding of the long-term fire history of the GYA is limited both geographically and temporally.

It is difficult to determine to what extent and in what fashion past and present policies towards fire influenced the 1988 Yellowstone fires. Certainly fire suppression between 1886 and 1972 resulted in a greater extent and continuity of flammable old-growth forests than would have occurred had all natural ignitions simply been allowed to burn. No systematic study of the consequences of suppression on the prefire landscape has been done. In a few locations past decisions to suppress fires must have influenced the behavior of 1988 fires. For example, had a wildfire that occurred in the northwest portion of the Park in 1978 been allowed to burn, the Fan Fire may not have spread. Certainly the spatial patterns of the 1988 fires will affect the behavior of future fires.

Geomorphic and Hydrologic Responses

The effects of fire on the hydrology and geomorphology of watersheds will be determined by spatial factors, such as topography, bedrock geology, soil conditions, and vegetational status, and temporal factors, such as seasonal and year-to-year patterns of precipitation. It is not possible to specify exactly the hydrological and geomorphological changes that will follow the 1988 fires in the GYA. Nevertheless, the following discussion outlines the range of possible responses and identifies the spatial and temporal factors that may result in particular outcomes.

Forest fire is a natural thinning agent of vegetation and changes the natural partitioning of surface and subsurface waters (Figure 1). This change, in turn, typically results in enhanced overland and channelized flow conditions (White and Wells 1979, 1981, Laird and Harvey 1986, Harvey et al. 1987a&b, Wells 1981, 1987). The impact of fire on runoff depends on the amount and timing of precipitation and the intensity of the burn. Runoff has been observed to increase by nearly an order of magnitude in extreme situations (Wells et al. 1987). The increase in runoff and its concomitant higher velocities result in higher peak discharges and accelerate erosional and sedimentation processes. Erosional processes vary from subtle sheet erosion to catastrophic debris flows. The maximum impact of these processes may occur within a year (White and Wells 1981) or may be manifested over several decades depending upon complex geomorphic responses (Laird and Harvey 1986).

Types and Spatial Distribution of Hillslope Processes Related to Fire

Rill and Sheet Erosion. Removal of vegetation and its retarding influence on overland flow, as well as decreased soil infiltration capacity, increase both rill and sheet erosion following fire. Rilling is common on steeper slopes (>10%) due to increased velocities of overland flow and incision into the soil. However, rilling is most common in areas of intense burns which typically display impermeable and/or water-repellent ash layers (White and Wells 1981, Wells 1981). Such areas were very limited in extent in the GYA fires (Shovic 1988). Factors which are likely to influence postfire erosion by sheet flow and rilling processes include infiltration characteristics of the ground surface, development of hydrophobic layers during the incineration of forest litter, the relative steepness of a slope, the erodibility of the soil, and the availability of sediment.

Infiltration rates on exposed soils can be decreased by rain-splash impact reducing the ground-surface porosity in response to plugging surface pores and fire-induced water repellency of the ground surface (Krammes and Debano 1965, Debano 1980). Campbell (1977) and White and Wells (1981) observed that water-repellent, or hydrophobic, layers were important in reducing infiltration rates in ponderosa pine ecosystems of Arizona and New Mexico, respectively. The water-repellent layer, which may occur a few millimeters below the ground

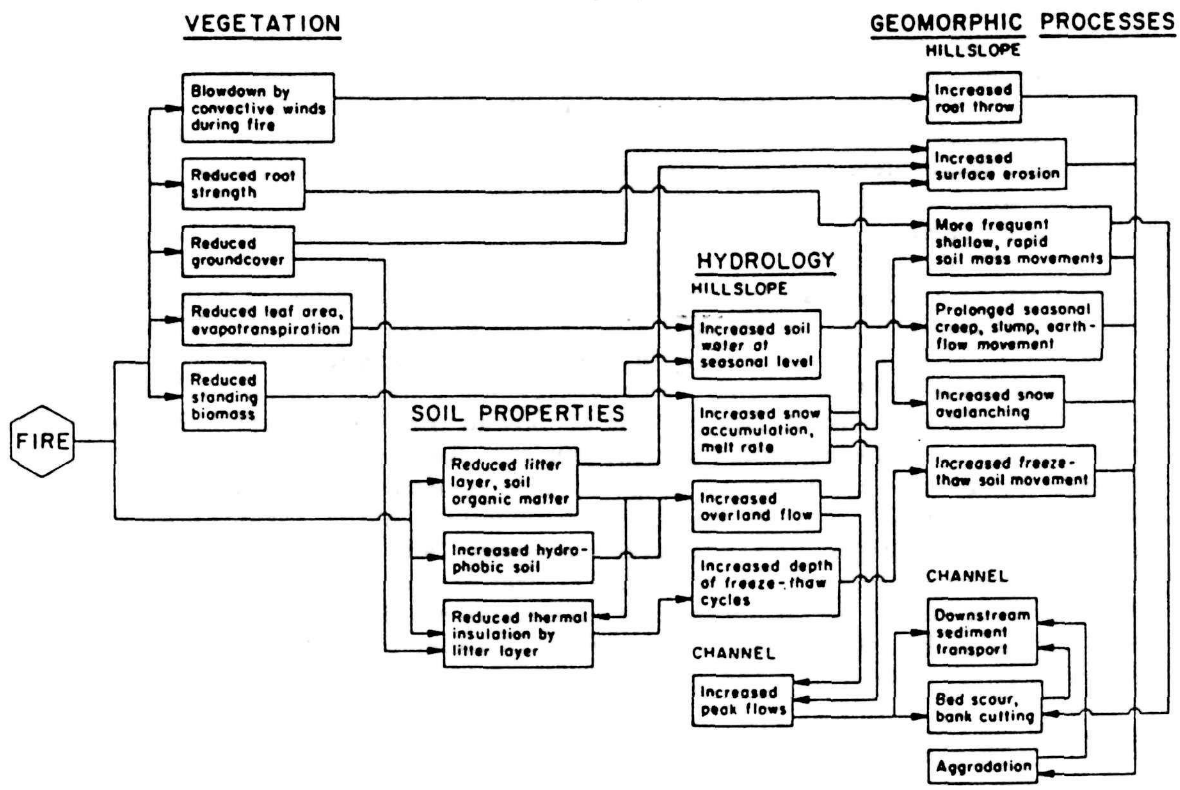

Figure 1. Effects of fire on vegetation, soil properties, hydrology, and geomorphic processes. From Swanson (1981).

surface, is composed of loosely packed (bulk densities of 0.5-1.0 g/cm^3) mineral grains and soil particles coated with organic molecules. The organic molecules form during the burning of forest litter and are driven into the soil where they inhibit soil water percolation (Debano 1980).

Hydrophobic layers have been observed to play an important role in developing extensive rill networks on hillslopes immediately after forest fires (White and Wells 1981, Wells 1981). Water infiltrates the surface layer and percolates downward until it reaches the repellent layer where the water accumulates and saturates the pore space. Increasing saturation results in increased pore pressure and eventually the layer liquefies, causing a small mass movement or slope failure (Wells 1987). The exposed water-repellent layer results in increased flow velocities and rilling.

Sheet erosion is a dominant erosional process on shallow gradient slopes and on those without hydrophobic soils. Sheet erosion results in a more even distribution of surface lowering than rilling and does not have the dramatic or visible aspects of rilling. However, unchannelized flow provides the vast majority of sediment supplied to ephemeral channels from hillslopes (Leopold et al. 1966).

Debris and Hyperconcentrated Flows. Recent studies have shown that debris and hyperconcentrated flow processes play an important role in the transport of eroded sediments from hillslopes (Wells 1987). Situations which are likely to promote erosion and sediment transport by debris flow processes include small, steep-gradient watersheds, availability of fine sediment, low vegetation density, and high rainfall intensity.

Postfire debris flows are common in small, steep watersheds and occur typically immediately after the fire. Debris flows apparently are caused by two processes, dry ravel and rilling, which contribute large sediment loads and runoff, respectively (Wells 1987). Dry ravel, a small landslide-like movement, delivers large amounts of sediment to channels where it is mobilized by the increased runoff related to rilling. Postfire debris flows differ from other types of debris flows in that they apparently do not require high rainfall intensities.

Debris slides from steep slopes (50%) are important sediment sources under some soil and geologic conditions. These events may lag a fire by several years or even decades as a result of the infrequency of slide-triggering storms and snowmelt events, and the timing of decomposition of tree roots which impart critical strength to soil on steep slopes.

Fire-Related Sediment Yields. Sediment yield from hillslopes increases in response to forest-fire devegetation. In areas of moderate to light burn, lower erosion rates and sediment yields may be reduced by postfire needlecast on denuded surfaces (White and Wells 1981). Conifer needles that are not consumed on the upper sections of trees are cast off after the fire and may provide a protective carpet that breaks the fall of raindrops and retards overland flow (Connaughton 1935, Megahan and Molitor 1975). These processes promote infiltration and trap fine sediment. In addition, needlecast influences the ground temperature and inhibits frost heaving, a process which increases sediment availability (White and Wells 1981). The impact of the needlecast on sediment yield depends upon the density of standing conifers and of dead, unburned needles.

The relationship between burn intensity and sediment yield is made less predictable as a result of other factors that affect sediment production (White and Wells 1981). Burrowing animals, such as gophers, disturb the ground surface and influence erosion. Postfire rehabitation and subsequent burrowing produce relatively large volumes of easily-transported sediment. In addition, the morphology of hillslopes and the relative position of the intensely burned areas influence sediment yield. For example, where fire is restricted to the upper part of long, gentle slopes, sediment delivery to streams may be greatly diminished (White and Wells 1981). Watersheds such as the Lamar River valley, with broad grassy valley floors and long alluvial fans, separate intensely burned regions from axial drainages. The rapid regrowth of grasses on these surfaces will probably inhibit the transport of fine sediment to the Lamar River. Also, larger watersheds have a greater sediment storage capacity, and sediment delivery decreases with increasing basin area.

Temporal Responses of Hillslope Erosion

Erosional processes are affected by seasonal and year-to-year climatic changes, most especially variations in rainfall availability and intensity. Winter snowfall inhibits surface runoff and erosion, but, rapid spring melting can dramatically increase the amount of runoff and concomitant erosion (White 1981). The volume and rate of snowpack melting will play a significant role in the immediate effects of a fire. A two- to three-fold increase in net erosion has been observed in relation to melting rate of snowpack within burned watersheds in other regions (White and Wells 1979).

A three- to eight-fold increase in erosion has been documented in areas of forest fires experiencing freeze-thaw processes. However, freeze-thaw processes may be influential in the destruction of the hydrophobic layers (White and Wells 1979), and thus may locally enhance infiltration. Factors that contribute to freeze-thaw processes include hillslope aspect, hillslope moisture regime, relative proportion of fine-grained material in the soil, and barren soil conditions.

Year-to-year climatic variations in the availability and intensity of rainfall can dramatically increase erosion and runoff in the years immediately following the fire. The paucity of quantitative studies on the climatic history of the Yellowstone region limits any interpretation concerning past and future climatic changes. Studies in other regions of the western United States have shown that these types of climatic changes dramatically increase runoff, and consequently erosion, and may be more significant than many human-induced perturbations to the natural system (Balling and Wells, in press).

Responses of Fluvial Environments

Hydrologic Responses. The behavior of the riverine, or fluvial, environments to postfire conditions is complicated by spatial and temporal diversity of runoff processes on the hillslopes. The immediate postfire response is increased local runoff on hillslopes; however, fallen trees and other types of forest fire debris can inhibit net runoff and erosion due to increased surface roughness, ponding, and local infiltration. The degree to which runoff will affect the large perennial channels is a function, in part, of the potential seasonal and longer-term climatic conditions.

Typically, hydrographs of recently burned watersheds differ from those of undisturbed watersheds in the partitioning of surface and subsurface water contributions to perennial channels. Postfire runoff is more flashy; that is, the flood peak is sharp with steep limbs. The postfire hydrograph typically has a greater surface-runoff component, whereas the prefire hydrograph has a greater base (ground-water) flow component. Vegetation and forest litter retard overland flow and enhance infiltration. The thinning of vegetation by fire and the development of water-repellent layers will enhance overland flow and net surface runoff. Thus, the less-frequent discharge events become larger in their magnitude, and flood events will cause greater geomorphic change. These hydrologic variations may persist for only a few years where burning was light or for decades where the fire was severe and/or vegetation recovery is especially slow. Reestablishment of prefire conditions will closely follow recovery of forest leaf area (Knight et al. 1985).

Geomorphic Responses. The increase in peak discharge and volume of flood waters in response to postfire conditions will result in increased sediment loads and may result in the permanent alteration of river channel morphology. An increase in the rainfall-runoff ratio by a factor of three significantly increased the sediment delivery from hillslopes to lower basin regions (Laird and Harvey 1986). Schumm (1977) has shown that increases in the transport of sand and larger sediment and in the mean annual flood will increase the channel width, width-depth ratio, and meander wavelength, but decrease the channel sinuosity.

As a consequence, channels may have a tendency to become morphologically unstable and braided under postfire conditions. An increase in sediment storage in the channels and the frequency of mid-channel bars may alter flow conditions locally within the channels. Harvey et al. (1987) have demonstrated that increased sediment delivery to channels results in a complex postfire cycle of degradation and aggradation of channels. Under these conditions, some reaches become protected with gravel and others fill with sand. Fine-grained sediment such as silt and clay typically are swept farther downstream and may contribute to increased suspended sediment loads over longer reaches of a river. This complex of responses of geomorphic systems to fires (contemporaneous aggradation and degradation) results from spatial and temporal changes in water-sediment inputs, as well as from alteration of the natural vegetational conditions (Laird and Harvey 1986).

Landscape Susceptibility to Postfire Conditions. Prediction of the postfire responses of the geomorphic and hydrologic systems of the Yellowstone area will be complicated because of spatial variations in surficial conditions and processes, and temporal variations in weather. Increased runoff, erosion, sediment yield, and geomorphic changes are part of a natural adjustment to postfire ecological changes. These processes have occurred naturally in response to prehistoric fires in the Yellowstone region, and a history of fire-related flood sediments should be developed for this area.

Specific regions of Yellowstone National Park will be more susceptible to postfire changes than other regions, and a map showing the susceptibility of landscape changes should be produced prior to 1989 snowpack melt. Such a map can be used to design and implement geomorphic and hydrologic research aimed at quantifying the postfire responses. For example, the Cache Creek region, which is characterized by small, steep watersheds and has a history of debris and/or hyperconcentrated flow conditions, will be an area vulnerable to postfire debris flow activity, increased runoff, and increased sediment delivery to the channels. Other areas such as the Lamar Valley may serve as sediment storage sites both on the valley floor and within the channel. Detailed monitoring of areas of different landscape susceptibility to postfire responses will aid in future predictions of the impact of fires on the natural hydrologic and geologic systems.

Soils and Belowground Processes

Fire effects on soils and belowground processes occur over a range of temporal scales. Some changes may be immediate as a consequence of direct heating, whereas others occur more slowly as a consequence of interactions between various ecosystem components. The range of potential effects of fire on any particular soil property or process is quite large and is dependent on prefire soil status, fire behavior, and postfire site history.

The soils in the GYA, as in most montane landscapes, are quite variable on spatial scales ranging from meters to kilometers. The specific effects of the 1988 fires and subsequent succession at any location will depend considerably on this variation. The vast majority of forest stands are underlain by soils which have undergone comparatively little chemical weathering and have only slight, if any, horizon development (Entisols and Inceptisols) (Southard 1975). Although these soils may vary considerably in depth and texture, they are typically coarse, well-drained, and poorly buffered against chemical change. The soils of grasslands and grass-shrublands (Mollisols) generally have more distinct vertical horizons, with the top or A-horizon typified by considerable organic material and underlain by a clay horizon. Forest soils that have well defined argillic (clay) horizons (Alfisols), occur in a few localities associated with particular parent materials (Munn et al. 1978). Alfisols and Mollisols generally are better buffered against chemical change than Entisols and Inceptisols.

Immediate Effects of Heating

The direct and immediate effects of fire on soils due to the combustion of organic material and heating of the mineral matrix may be dramatic at the soil surface. However, such effects generally were negligible at depths below a few centimeters (Shovic 1988). The depth to which the soil is modified depends largely on the duration and intensity of soil heating. Because of uneven soil heating and ash deposition, the properties of soils affected by fire will vary across a burned landscape. Thus, fire-caused changes in soil properties vary considerably from one part of a burned area to another.

Soil heating beneath forest Entisols and Inceptisols was quite variable. Situations where soil heating was classified as "high moderate" or "high" (nearly complete combustion of soil litter and humus layers) were quite localized and usually associated with local "fire storms" or areas of high fuel accumulation. The limited fuel accumulation above grassland and shrubland soils resulted in uniformly light soil heating. Organic peats or Histosols occur in some moist meadow areas. Because of the drought conditions of the 1988 summer, many of these soils were sufficiently dry to burn. Although such situations were highly localized, the impacts on these sites may be dramatic.

It is unlikely, except under the most extreme heating, that the fires altered soil textural characteristics (i.e., the amount of sand, silt, and clay) of soils. However, the loss of the surface organic matter, particularly in coniferous forests, may dramatically alter soil physical characteristics. The loss of humus may result in some reduction of water infiltration and could alter nutrient exchange capacity on sites where soil heating was intense. However, loss of humus was confined to the upper few centimeters of the soil horizon in most cases.

Soil Microclimate

One of the most obvious consequences of the removal of the forest canopy and forest floor fuel by fire is alteration of the soil surface radiation budget. In general, soils in burns tend to warm sooner and to a greater extent than soils beneath intact vegetation. Heat gain may also be increased as soil albedo (reflectivity) is lowered owing to blackened soil surfaces. These effects, independent of other fire-caused environmental changes, have been found to be directly responsible for increased plant production following fire in a variety of ecosystems (Old 1969, Sharrow and Wright 1977). Furthermore, these microclimatic changes also increase microbial activity and, thereby, the rate of nutrient mobilization.

Fire-caused changes in soil surface microclimate can adversely affect plant growth. For example, the absence of plant cover also results in increased heat loss due to reradiation during the night. Thus, burned areas often experience considerably greater diurnal temperature fluctuations than unburned areas (Wilbur and Christensen 1989). Furthermore, high irradiance such as occurs at high elevations and on south-facing slopes can result in excessive soil heating.

Soil Nutrients

Fire can affect virtually every soil chemical factor. However, the nature and extent of these effects are highly variable and attenuate very rapidly with soil depth. Variations in prefire vegetation, soil fertility, patterns of ash deposition, and postfire environment are among the factors influencing the nature of fire-caused changes in soil chemistry. Predictive models of these relationships are incomplete or nonexistent (Raison 1979, Woodmansee and Wallach 1981, Christensen 1987).

Char and ash produced from wildland fires often contain large quantities of mineral nutrients necessary for plant growth, although not necessarily in an immediately usable form. Concentrations of available cations (Ca, Mg, and K) as well as phorphorus may be relatively high. However, most nitrogen and much of the phosphorus in ash and char are in organically bound forms (Tryon 1948, Raison 1979, Christensen 1987). Although available forms of nitrogen and phosphorus (ammonium, nitrate, and ortho-phosphate) are not abundant in ash, organic forms are mineralized rapidly to produce them (Jurgensen et al. 1981). The addition of cations to soil from ash can potentially increase soil pH (e.g., Ahlgren 1960, Viereck and Dyrness 1979), which often favors microbial activity and availability of some nutrients (Raison 1979). This could be especially important in the poorly buffered, acidic soils of burned conifer stands. Soils in such stands are acidified by the decomposition of coniferous litter as well as the high content of sulfur in the many of the parent materials of the GYA. Where ashfall was light, as in burned grasslands and light surface fires beneath forest canopies, nutrient changes directly due to ash fall may be undetectable (Daubenmire 1968). Nevertheless, microclimatic changes in these situations may make nutrients more available.

Although fire may increase availability or mobility of important mineral nutrients, it also decreases the total ecosystem capital of such nutrients. Immediate losses of nutrients due to volatilization and smoke (particulate loss) vary among nutrients and with fuel characteristics and fire behavior. For example, the proportion of total fuel nitrogen lost to volatilization may be less than 20% for woody fuels, but as high as 70% for fine grassland fuels (DeBell and Ralston 1970, Sharrow and Wright 1977, Christensen 1975, 1977, 1987). Such losses are considerably less for elements such as phosphorus and most cations. Although addition of mineral nutrients and higher rates of mineralization associated with fire may increase soil fertility, they also render these nutrients more susceptible to loss by leaching and surface runoff (Knight et al. 1985).

It is possible that, as the initial pulse of available nutrients is exhausted during the early successional stages, nutrients may become even more limiting than before burning as a consequence of these losses to total nutrient capital. However, normal nutrient inputs from weathering and atmospheric depositition, in addition to the potential for fire-enhanced rates of some input processes such as nitrogen fixation (e.g., Jorgensen and Wells 1971), appear to be sufficient to compensate for nutrient losses during the normal fire cycle (Fahey et al. 1985, Fahey and Knight 1985).

The increase in nutrient availability following burning, regardless of its magnitude, is often a comparatively brief phenomenon. Indeed, nutrient pulses attributed to burning often are confined to only the first or second growing season following fire (Jurgenson *et al.* 1981, Fahey *et al.* 1985). Interventions, such as seeding of short-lived alien species for erosion control, may delay the establishment of native species and thereby prevent them from taking advantage of this nutrient pulse. Thus, such activities should be undertaken only where they are clearly warranted.

Biological Features of the Soil

The fire-caused death of plants will result in considerable belowground carbon in roots becoming available to saprophytic organisms such as bacteria and fungi. The addition of organic matter as partly ashed residues as well as the addition of nutrients in ash will further accelerate the activity of these organisms (Jurgensen, et al. 1981). The postfire soil environment also is often favorable for growth of nonsymbiotic nitrogen fixing microbes and nitrifying bacteria (Jorgensen and Wells 1971, Jurgensen et al. 1979, Harvey et al. 1984).

Many of the mushroom-forming fungi in forest and shrubland soils form symbiotic relationships, or mycorrhizae, with the roots of higher plants. So-called ectomycorrhizal associations are essential for normal establishment and growth of many conifers. Although postfire conditions may favor the growth of fungi involved in these associations (Harvey et al. 1980a,b), ectomycorrhizal fungi are not tolerant of sustained drought. Thus, the establishment and growth of plants that are dependent on such mycorrhizae may depend on interactions between weather patterns and fire-caused soil changes which we cannot currently predict.

Where soil temperatures were especially high or the duration of heating unusually long, soils may be sterilized and postfire microbial populations may be significantly reduced (Ahlgren and Ahlgren 1965, Dunn and DeBano 1977). Tree establishment and growth may be poor or absent on such sites. However, such intense soil heating was generally confined to rather small sites such as burnt logs. Microbial recolonization will likely be rapid from adjacent moderately burned areas.

The soil and microclimatic conditions following fire favor the establishment and growth of a variety of native herb and shrub species. The root systems of these plants are important in stabilizing soils on steep slopes and the products of their eventual decay replace soil humus lost in the fire. Symbiotic nitrogen fixing herbs, such as clover (*Trifolium*) and lupine (*Lupinus*), and shrubs, such as *Ceanothus*, *Shepherdia*, *Alnus*, and *Purshia tridentata*, are often quite abundant in recently burned areas in the GYA (White and Williams 1985). Burning may also enhance the activity of nitrogen fixing cyanobacteria (Jorgensen 1971). These species are thought to play an important role in the replenishment of nitrogen capital lost during burning. Interventions such as seeding of alien species or artificial reforestation programs could discourage the growth of this important group of species.

Aquatic Ecosystems

Very few studies have examined the effect of fire on the aquatic biota (Lotspeich et al. 1970, Albin 1979, Hoffman and Ferreira 1976, Minshall et al. 1981) and none has adequately addressed major aspects of aquatic ecosystem function. The limited work thus far has been directed mainly at determining the effects of fire on water chemistry (Tiedemann et al. 1979, Schindler et al. 1980). Nevertheless, it is possible to develop a set of predictions regarding the immediate, near, and long-term consequences of the 1988 fires by supplementing the existing information base on fire response with knowledge of the response of aquatic systems to clear-cutting and physical disturbances within the channel and of their general ecological behavior.

The impact of fire on aquatic ecosystems will vary with size, aspect, slope, and bedrock geology of watersheds, severity of the fire, and climate. Given the patchy nature of the recent fires in Yellowstone, the greatest impacts probably will be seen in the smaller, more severely burned watersheds where the effects of the fire will be magnified, and the buffering capacity (thermal dispersion and chemical dilution) of the water will be lowest. As larger and larger watersheds are considered, greater percentages of the area will remain unburned, and greater volumes of water feeding the lakes and streams will serve to diminish the effects of the fire.

The smaller (headwater) watersheds in the GYA tended to burn severely or not at all. Although a significant number of such watersheds burned, it was by no means the majority. None of the larger drainages in the GYA burned in its entirety and, because of the reduced direct impact and dilution effect from a mix of upstream sources, discernible immediate or long-term adverse effects probably will not be seen. It is difficult to find watersheds in Yellowstone greater than third order in size which suffered substantial impact over their whole areas (Minshall pers. observ.). We are aware of only two (Cache Creek, Hellroaring Creek) watersheds where this is the case, and only a few others (e.g., Upper Lamar River, Slough Creek) that might possibly fall into this category. Most of the streams in Yellowstone that support a major sport fishery (Firehole, Gardner, Gibbon, Lamar, Madison and Yellowstone) are all 5th order or greater. None of the larger lakes in the Park (Yellowstone, Shoshone, Lewis, Heart) had major portions of their watersheds severely burned.

Most of the potential problems resulting from the fires are expected to occur due to accelerated runoff from snowmelt during the spring of the first few years following 1988. The high discharge and erosion could result in substantial impact, particularly in steep heavily burned areas exposed to rapid snowmelt (e.g., south facing) and where moisture infiltration capacity is low. Greater potential for damage of this sort lies with streams draining burned watersheds in the Absaroka Mountain Range. Significant increases in erosion, turbidity and sediment loads, along with channel movement, are likely to occur in these areas and may result in substantial decreases in algal, insect, and fish populations. Considerable recovery is likely to begin after the first few years as the redevelopment of terrestrial vegetation begins to slow the rate of surface runoff. However, even in moderately impacted areas, three to ten years may be required (depending on local weather conditions and the rate of forest recovery) for significant recovery of the stream ecosystems to occur. In more severely impacted watersheds with shallow soils, low terrestrial plant regrowth, and/or heavy precipitation, return to prefire conditions might require 50 years or more. However, it should be noted that the most susceptible watersheds in this regard were already subject to substantial physical disturbance from sediment and high flow prior to the fire (Mohrmon et al. 1988); consequently, the added impacts due to the fire may be much less dramatic than otherwise expected.

The severity of fire effects on a watershed is a function of the fire's intensity and percentage of the watersheds burned. The greater the severity, the greater the potential for alteration of an aquatic ecosystem from its prefire condition. Aquatic habitats in or adjacent to forested areas will be more severely affected than those buffered by meadows or other wetlands. Many of the latter should experience no lasting adverse effects, but vegetative growth may be stimulated following the fire due to the release of nutrients formerly bound up as plant biomass. As mentioned earlier, aquatic habitats in smaller forested watersheds are potentially more susceptible to adverse effects than those in larger or less wooded watersheds because of the patchy nature of the Yellowstone fires and because of the reduced buffering capacity of the smaller volumes of water.

Fire-caused alterations of patterns of runoff may adversely affect aquatic populations which lack the reproductive capacity to adjust to them. Increases in flow magnitude could destablize stream systems and, at least over the short-term, could decrease biotic diversity and production (Resh et al. 1988). In the long term, however, such changes probably are well within the range of conditions periodically experienced by aquatic organisms and no lasting damage should result. Such disturbances are all part of a grand erosional-depositional "cycle" (Chorley et al. 1984) associated with periodically recurring fires (Arno 1980, Houston 1973, Romme and Knight 1982), to which the organisms must have been able to adapt or they would not have survived to the present. In fact, in the broader perspective (see later), the fires could actually enhance biotic production over prefire conditions if nutrient inputs increase. Chance storm events (e.g., heavy snowpack, rapid snowmelt on frozen ground, spate, summer drought) can magnify damage, impede regrowth, and set new (lower) population levels in burned watersheds, just as they do in undisturbed ones.

The consequences of fire to aquatic ecosystems can be partitioned into (1) "immediate" effects arising directly from the fire (e.g., increased temperatures, altered water chemistry, abrupt change in food quality) and (2) delayed impacts resulting from the removal and eventual successional replacement of the terrestrial vegetation. Some of these delayed effects are created by physical disturbances within the first year after fire associated with increased runoff. In addition, longer-term alterations associated with the removal and recovery of the riparian and terrestrial vegetative cover and consequent alteration of food resources and retention capacity in the stream may be expected (Minshall et al. 1981, Molles 1982, Likens and Bilby 1982).

Immediate Effects

Except in very small water bodies (e.g., 1st order streams and small seeps), it is unlikely that the heat from the Yellowstone fires did much damage to the aquatic biota because of the high specific heat of water and replenishment from cool groundwater sources. Cushing and Olson (1963) recorded a $10^{o}C$ increase in temperature for a very short period of time in a small (2 m wide x 25 cm deep) slow-moving stream following the burning of weeds which covered the stream and its banks. Trout (*Oncorhyncus mykiss*, formerly known as *Salmo gairdneri*) in live boxes showed marked distress but did not die. Heat-fracturing of the surfaces of rocks in 1st order streams and incineration or scorching of exposed and shallowly submerged aquatic plants have been observed in Yellowstone (Minshall pers. observ.). However, in most cases heating of the water by the fire of only a few degrees is to be expected (Albin 1979, Ice 1980). In larger streams, shading by dense clouds of smoke actually may have reduced water temperatures over those experienced on a clear day (Ice 1980, T. Koch pers. observ. on Firehole River).

Based on previous investigations, few if any adverse effects of the Yellowstone fires on water chemistry are to be expected (Johnson and Needham 1966, Tiedemann 1973, McColl and Grigal 1975, Hoffman and Ferreira 1976, Wright 1976, Tiedemann et al. 1978, Albin 1979, Schindler et al. 1980, Stottlemeyer 1985). In fact, temporary stimulation of algal growth at levels generally considered to be beneficial may be expected in some cases (McColl and Grigal 1975, Albin 1979). However, mortality of fish has been observed in some 2nd and 3rd order streams in Yellowstone (Minshall pers. observ.) which may be caused by increases in certain ions due to ash entering the water (Cushing and Olson 1963). In such areas the fire may have burned more intensely and thoroughly than those previously studies (Schindler et al. 1980). Increased pH may directly affect aquatic organisms or may act indirectly by enhancing the toxicity of certain substances (e.g., ammonia) (Rand and Petrocelli 1985). On limited reaches of some streams (e.g., Little Firehole River), significant mortality of fish resulted from accidental drops of fire retardant into aquatic habitats (T. Koch pers. observ.).

Delayed (Secondary) Effects

The delayed consequences of fire on aquatic ecosystems in Yellowstone may be separated into near- and long-term effects. Most of the adverse near-term effects are likely to be associated with increased turbidity and sediment levels and stream channel movement. Because of dilution, delayed detrimental influences on water chemistry are not expected, but increased loading of nutrients in severely burned watersheds may result in enhanced production of algae, possibly extending over a period of two to three years. Opening of the forest canopy may result in increased water temperatures, particularly in headwater streams, and may have a detrimental effect if critical heat thresholds of resident invertebrate and fish populations are exceeded. However, it is more likely that the slight increases expected in most cases, coupled with increases in light and nutrients, will result in increased primary and secondary production.

Most of the long-term responses of Yellowstone aquatic ecosystems to the 1988 fire are likely to be closely allied with the recovery (succession) of the forest and understory vegetation (Ross 1963, Hynes 1975, Vannote et al. 1980, Minshall et al. 1981, 1983, 1985, Molles 1982, Likens and Bilby 1982). Cummins et al. (1983) have emphasized the importance of episodic events of greater-than-annual time scales, such as fires, to material fluxes in stream ecosystems. Such events often serve as "reset mechanisms" for long-term temporal responses in streams. Molles (1982) postulated a long-term recovery to prefire levels of the shredder functional feeding group of Trichoptera, paralleling the accumulation of conifer wood and forest litter in streams associated with postfire forest succession. Recovery of the forest cover should result in increased shading of streams and ponds and decreased input of nutrients over time. Eventually, conditions in these habitats should return to prefire levels. But, in the intervening period (once turbidity and sediment loads originating from the fire have diminished sufficiently) conditions could be such that production of algae, invertebrates, and fish will be enhanced over that found before the fire.

Plant Successional Patterns

The importance of past fires in shaping vegetation patterns in the Greater Yellowstone Ecosystem is clear (Taylor 1969, 1973, 1974, Habeck 1973, Houston 1973, Loope and Gruell 1973, Gruell and Loope 1974, Despain and Sellers 1977, Arno 1980, Romme 1982, Romme and Knight 1982). Many of the forests are even-aged and dominated by lodgepole pine, a species that invades readily after a burn (Perry and Lotan 1979). Also, charcoal is easy to find in the surface soil and fire-scared trees are common. The boundaries of old fires form a mosaic of young and old forests delineated by sharp transitions that are quite apparent in aerial views of the GYA landscape.

The obvious adaptations to fire seen in many of the native plants testify to the long-term role of fire as a selective force on this landscape. For example, the serotinous (closed) cones of lodgepole pine allow this species to take advantage of the abundant water, nutrients, and space made available immediately following a burn (Lotan 1975, Muir and Lotan 1985a, b). Such cones allow for the accumulation and storage of large quantities of seed in the trees during the years between fires. The heat of a fire cracks the resin bonds on the cone scales, releasing seeds at that point in the fire cycle when successful establishment is most likely. Very few of the seeds are burned. This feature contributes to the development of relatively even-aged stands in the Rocky Mountains where fires are frequent. The connection between fire and cone serotiny is emphasized by the fact that, where windthrow or insect pathogens are more important than fire or where the last major disturbance was caused by factors other than fire, more of the lodgepole pine have non-serotinous cones (Muir and Lotan 1985a).

Further evidence for a long history of fire is the fact that nearly all of the grasses, forbs, and shrubs are capable of sprouting from belowground buds. Parts of the plants above the soil surface may be charred or even completely burned, but much of the root system remains unharmed because soil temperatures below a centimeter or two usually are not elevated to lethal levels (Wright 1971, Shovic 1988). Energy reserves in the surviving root systems allow for the production of new stems and leaves within a year, if not sooner. Aspen also is capable of sprouting and may even increase in abundance following fire due to the sprouting adaptation alone (DeByle et al. 1987). Aspen regeneration by seed is rare (McDonough 1985). These and other adaptations suggest that the plants of Yellowstone and the region have evolved in the presence of fire.

Patterns of Change

The 1988 fires will result in major changes in the Yellowstone vegetation. Old forests that burned will be replaced by young forests, shrublands, or meadows. The total land area dominated by Engelmann spruce and subalpine fir may be reduced, primarily because neither of these species produces serotinous cones or is capable of sprouting. However, such forests account for a small proportion of the area burned in 1988. Big sagebrush abundance may decrease because it is does not sprout following fire. Grasses, sedges, and forbs are likely to dominate in place of spruce, fir, and big sagebrush until the trees and shrubs become reestablished. Where the fires were less intense and many of the trees survived, open woodland or savanna may result. This situation is most likely in Douglas-fir forests, as mature individuals of this species have thicker bark than the other trees species and often are able to survive surface burns. Extensive Douglas-fir forests are common only in the northern parts of the GYA.

Succession is easiest to predict where sprouting growth forms were dominant prior to the fires. Thus, burned aspen groves should respond quickly, creating an abundance of young aspen sprouts (Jones and DeByle 1985). The associated grasses, sedges, forbs, and shrubs also will sprout. The physiognomy of the groves will be altered dramatically, with a high density of young sprouts instead of widely-spaced older trees, but the aspen can be expected to grow rapidly. Young sprouts of aspen are preferred browse for many ungulates. Because the population density of browsing mammals is exceptionally high at this time, they could have an unusually heavy impact on aspen regeneration patterns (Gruell and Loope 1974). On the other hand, the fires may have created ideal conditions for the restoration of vigorous aspen groves. The interactive effects of fire and browsing on aspen regeneration is a topic of considerable interest that is not fully understood.

In riparian meadows and shrublands the plants should resprout vigorously and changes will be mainly physiognomic (Leege 1969). Browsing may increase because of the increased abundance of more succulent (possibly more nutritious) sprouts. As with the aspen groves, scientists have the opportunity to observe recovery in the presence of large ungulate populations and to ascertain just how well the plants are adapted to high levels of herbivory.

Sagebrush-grasslands are common in some parts of the GYA and probably were altered more dramatically than the riparian vegetation and aspen groves. Big sagebrush, often the dominant plant, cannot resprout and thus is greatly reduced in abundance following fires (Blaisdell 1953, Billings 1989). Sprouting grasses and forbs typically increase until new sagebrush seedlings become established and grow to maturity, perhaps 15 to 30 years later. Big sagebrush can be an important winter food for deer, elk and pronghorn antelope. The impact of this food loss remains to be seen. Nearly 14,000 ha or about 9% of the GYA's sagebrush-grassland burned.

During the next few decades, the effects of the fires will be most easily seen in the coniferous forests. None of the coniferous trees in Yellowstone has the ability to sprout. Except where aspen coexisted with conifers, forest regeneration depends on a seed source and seedling establishment. If even a few suppressed aspen existed in a stand prior to burning, it is likely that such a stand will be converted temporarily to aspen (DeByle et al. 1987). This occurs because the aspen root sprouts grow more rapidly than young conifer seedlings. Through time, the spruce, fir, and pines may again become dominant over the aspen, relegating it again to a subordinate role in the community until the next major disturbance, but this process may take a century or more. Thus, the total area occupied by aspen forests may increase because of the fires.

Forest regeneration will be slower where aspen was not present in the coniferous forests. Initially the grasses, sedges, forbs and shrubs will form a dense vegetative cover under the standing trees killed by the fire (Despain 1977). Species composition will vary greatly, as will the amount of cover. Typically the herbaceous plants will appear unusually green and lush, an indication of improved water and nutrient availability. Tree seedlings will become obvious after 5-10 years and may even be very dense if serotinous lodgepole pine dominated the pre-burn forest. Where the pines were not serotinous, or where spruce and subalpine fir dominated, seedlings and sapling may be sparse for one or more decades. In areas that are marginal for tree growth or where fires were especially intense, succession may not proceed beyond the formation of meadows (Stahelin 1943). Some meadows in the GYA landscape today may have been created in this fashion. Such meadows provide important wildlife habitat and can enhance landscape diversity in an aesthetically pleasing way.

Conifers will become re-established over most of the burned coniferous forests. Lodgepole pine and/or Engelmann spruce probably will be the most common dominants in the young forest, with Douglas-fir well represented in the low elevation areas. These three species are best adapted for seedling establishment on mineral soil in open areas (Alexander 1987). Standing dead trees from the 1988 fires will be conspicuous for 20 years or more. Lodgepole pine and Engelmann spruce will continue to become established in the understory as seed availability and understory environmental conditions permit (Peet 1988). Subalpine fir and, in some areas, whitebark pine will establish and share dominance with the lodgepole pine and spruce after 50 to 100 years. Lodgepole pine may be replaced eventually by spruce and fir, although many forests succeed to mixtures of these species. In some environments lodgepole pine may persist until the next disturbance, sometimes forming uneven-aged stands (Despain 1983, Whipple and Dix 1979). Elsewhere spruce and fir may be the dominants from the very beginning of forest regeneration.

In general, the effects of the fire on the terrestrial vegetation of the next few decades will be: 1. a larger portion of the area in meadows and young forests; 2. aspen forest over a larger area, though probably still a small portion of the Park; 3. less sagebrush in some areas for a decade or more; and 4. more luxuriant herbaceous vegetation for several decades.

Ecologists have all but abandoned the once popular theory that successional change following disturbance leads inexorably and deterministically to particular climax endpoints. The total number of possible permutations of successional pathways is quite large and will depend on such factors as burn intensity and size, seed availability, abundance of sprouting growth forms, topographic and soil characteristics on specific sites, and, climatic conditions in the next few years. Succession is strongly affected by stochastic events which vary greatly from place to place; consequently variation in successional sequences is considerable (Stahelin 1943, Romme and Knight 1981). Much of the variation that will characterize patterns of recovery over the next few decades will be a consequence of the vegetation diversity that existed in Yellowstone prior to the 1988 fires. This landscape diversity will be enhanced as the mosaic of successional patterns is superimposed on the burn mosaic and as the process of successional change continues in the forests that were not burned in 1988.

It is tempting to suggest that the vegetation mosaic has been restored to some condition that existed hundreds of years ago. However, insufficient data are available to make such an assertion for the entire Park. We can state with confidence that the mosaic has changed before due to fire and other factors (Romme 1982). The Yellowstone National Park of 2072 will not be the same as 1872, just as the landscape of 1872 was unique compared to previous times. Even without human influences (of which there have been many; Haines 1977) Yellowstone landscapes would continue to change if for no other reason than climatic changes and the continued evolution, immigration, emigration, and even possible extinction of plant and animal species. Big changes occurred in 1988, and it seems safe to assume that such changes will occur again in the future. Indeed, such change is the *sine qua non* of wilderness.

Terrestrial Biodiversity

The biotic diversity of an area such as the GYA is a consequence of variability at three levels of organization. 1. *Landscape diversity* refers to variation *among* assemblages of species at different locations and times. Areas with similar environments may have similar (but never identical) species composition and, therefore, low landscape diversity. Spatial variation in the physical environment and patterns of disturbance results in considerable variation in species composition from locality to locality. Historical patterns of disturbance have been shown to be an especially important source of landscape diversity in Yellowstone. 2. *Species diversity* is used here to refer to diversity *within* communities or assemblages of species. Species diversity actually consists of two components, the number of species ("richness") and the evenness of their relative abundances ("equitability") (Whittaker 1972). Although considerable theoretical discourse has been devoted to this latter component of species diversity, species richness has been the primary concern of most management programs and will be the central focus of this discussion. 3. *Genetic diversity* has two components, the diversity of gene pools within a species and the diversity of genetic information within these gene pools. Because little is known about the genetic structure of most species within the Greater Yellowstone Area, little can be said regarding this aspect of biodiversity.

Landscape Diversity

The importance of natural disturbance processes, including fire, in the maintenance of landscape diversity in the Greater Yellowstone Area has been thoroughly documented (Patten 1963, Houston 1973, Romme 1982, and Knight 1988). Although the physical environment of much of the Yellowstone Plateau is relatively homogeneous, disturbances such as fire, wind, and insects have created a patchwork mosaic over a range of spatial scales. As emphasized in several of the above sections, the high degree of spatial variability in fire behavior in the 1988 fires will result in tremendous spatial variability in environment and trajectories of postfire recovery. Thus, the diversity of species assemblages probably will be enriched.

Species Diversity

The heterogeneous post-burn landscapes that will develop in much of the greater Yellowstone area may decrease abundances of rare interior species. However, increased abundances of species favoring edges and those requiring two or more habitat types can be expected (Franklin and Forman 1987). In general, the fires may result in increased rarity of the relatively few species that require extensive areas of unbroken, mature forest, but there may be increases in the abundances of species characteristic of edges or earlier successional stages.

Plants. The understory vegetation in the early postfire stages of succession is generally more diverse in species composition than is common in later stage forests (Taylor 1973). The adaptations that favor establishment or persistence of many plant species in lightly to moderately burned areas have already been discussed. In severely burned areas, re-establishment will result from long-distance dispersal, and proximity to unburned areas will determine the rate of reestablishment. Thus, it is conceivable that species diversity might be reduced initially in some areas far from sources of seed.

Only one rare endemic, *Agrostis rossae*, occurs in Yellowstone. Because this plant is found only in geothermal areas, it is unlikely that the fires have affected its populations.

An unwanted increase in plant species diversity may occur with the invasion of exotic weeds, especially if artificial seeding occurs. Normal forest seed mixes contain perennial exotics incompatible with the preservation of natural systems. Weaver and Woods (1985, 1986, Weaver et al. 1989) list exotic plant species able to establish in disturbed sites in Glacier and Grand Teton National Parks. The exotics of greatest concern in the Yellowstone area are probably Canada thistle (*Cirsium arvense*), timothy (*Phleum pratense*), and yellow sweetclover (*Melilotus officianalis*). These species occur throughout the burned areas and could dominate the seral vegetation, at least locally. Although knapweed (*Centaurea maculosa*) probably will not grow in higher elevations in the burned area, it can invade lower-elevation sites. Quackgrass (*Agropyron repens*), crested wheatgrass (*Agropyron cristatum*), Kentucky bluegrass (*Poa pratensis*), and butter and eggs toadflax (*Linaria vulgaria*) also can invade at lower altitudes. Monitoring should be done to prevent large-scale invasions by these species.

To limit the abundance and spread of alien weeds, burned areas should be monitored, especially where roads cross burned areas or where roads, trails, or fire lines enter burned areas. Many alien species escape from roadside planting of commercial seed mixes used for soil stabilization. Thus, weed-free mixes of local ecotypes of native plants should be used in any artificial revegetation program.

Terrestrial Invertebrates. Very little is known about the diversity of terrestrial invertebrates in the GYA. However, they are extremely important ecologically, both in grazing and detritus food chains. Although there probably was heavy fire-caused mortality in many species, most terrestrial invertebrates are highly vagile and will recolonize appropriate habitat quickly. One particular group that is likely to increase in abundance if not diversity is the Cerambycidae, or long-horned beetles. Cerambycids bore into dead or dying timber and are very important agents for initiating the process of wood decay in forest ecosystems. Because they often attack fire-stressed lodgepole pine trees, populations of the mountain pine beetle (*Dendroctonus monticola*) and ips beetle (*Ips* spp.) probably will increase (Knight 1987).

The most recent list of GYA Lepidoptera species includes 89 species of butterflies and skippers. Most of these species are in the sagebrush/grassland community complex and in alpine meadows. Many butterflies and skippers depend on early successional species for either larval food plants or adult nectar sources, so the fires probably will result in increased resource availability for these species. A northern Rocky Mountain endemic butterfly, the Yellowstone Checkerspot (*Euphydryas gillettii*) occurs in the Park and surrounding regions. It was uncommon prior to the 1988 fires, and its populations may be in decline. For example, Williams (1988) visited 29 localities where the species had been collected in the past and found extant populations at only 13 of them. Part of this decline may be attributable to fire suppression. The species' larval foodplant, *Lonicera involucrata*, will grow wherever sufficient moisture is available. However, the caterpillars can only complete their development on *Lonicera* plants that are growing in direct sunlight. These rather precise habitat requirements are most often found where moist mountain meadows meet lodgepole or spruce/fir forests. In the absence of fire, however, the forest begins to encroach on the meadow, shading the *Lonicera* and eliminating the warm microhabitat necessary for the butterfly (Williams 1981, 1988). The Yellowstone fires may have caused some direct mortality of *E. gillettii* if they burned through extant populations. On the other hand, the fires will be advantageous for the species in the long run by arresting succession and creating new habitat.

Amphibians and reptiles. Four species of amphibians and four species of reptiles have been recorded from Yellowstone National Park (Baxter and Stone 1985). The tiger salamander (*Ambystoma tigrinum*), spotted frog (*Rana pretiosa*), chorus frog (*Pseudacris triseriata*), and garter snake (*Thamnophis elegans*) are widely distributed in riparian habitats. The boreal toad (*Bufo boreas*) is dependent on these habitats for breeding, but ranges more widely during the non-breeding season. Being less mobile than larger vertebrates, these species may have suffered some direct mortality as a result of the fires. However, there is no reason to believe that populations of these organisms will not rapidly recover.

Disjunct, isolated, populations of the sagebrush lizard (*Sceloporus graciosus*) occur in geothermal areas in the Park. It is highly unlikely that these were affected by the fires. There is one Yellowstone record for the short-horned lizard (*Phrynosoma douglassii*) and for the bull snake (*Pituophis melanoleucas*) (Baxter and Stone 1985). These species usually occur below 1980 and 1830 m respectively, but it is possible that small populations may exist in the lower elevations of the greater Yellowstone area. The effect of the fires on these populations is impossible to assess.

Although Baxter and Stone (1985) include the Yellowstone area within the ranges of the northern leopard frog (*Rana pipiens*) and the rubber boa (*Charina bottae*), no Park records exist. Thus the pre-fire and post-fire status of these species is completely unknown.

Birds. Breeding birds may display some of the most dramatic responses of any animals to the 1988 fires. Taylor (1973) suggested that densities of breeding birds in lodgepole pine forests should change from fewer than 20 pairs per km^2 in the old, unburned forest, to around 100 pairs per km^2 in forests that are about 25 years old. His conclusion that lodgepole pine forests must be periodically burned to promote greater biotic diversity is typical of many investigations in these types of forests, and is applicable to many habitats found throughout the Yellowstone region.

A number of changes in bird densities can be predicted, based on their life history attributes. For example, there will be increases in number of common bark-foraging species such as hairy woodpeckers (*Picodes villosus*), red-breasted nuthatches (*Sitta canadensis*), and brown creepers (*Certhia americana*), and of rare species, particularly black-backed (*Picoides arcticus*) and three-toed woodpeckers (*Picoides tridactylus*), as they respond to the increase in insect populations attracted to areas with fire-killed trees. Likewise, there will be local increases in the density of a few species which prefer open habitat to closed canopy forest (e.g., Townsend's solitaire, *Myadestes townsendi*). Barrow's goldeneyes (*Bucephala islandica*), mountain bluebirds (*Sialia currucoides*), tree swallows (*Iridoprocne bicolor*), flickers (*Colaptes auraus*), house wrens (*Troglodytes aedon*), dusky flycatchers (*Empidonax oberholseri*), ospreys (*Pandion haliaetus*), and other snag and cavity-nesting species are also likely to increase as a result of increased nesting sites provided by standing dead trees.

Species that prefer undisturbed forest habitat and may suffer some local population declines include the great gray owl (*Strix nebulosa*), yellow-rumped warbler (*Dendroica coronata*), Swainson's thrush (*Catharus ustulatus*), ruby-crowned kinglet (*Regulus calendula*), western tanager (*Piranga ludoviciana*), and pine siskin (*Spinus pinus*). However, no losses of these or other forest habitat specialists from the GYA are anticipated.

In the event that major spring floods cause high sediment deposition and major fish and invertebrate kills, some birds that feed upon these organisms may be affected. These include the osprey, the harlequin duck (*Histrionicus histrionicus*), and the dipper (*Cinclus americanus*).

Rare, threatened and endangered birds in the greater Yellowstone region include the bald eagle (*Haliaeetus leucocephalus*), the peregrine falcon (*Falco peregrinus*), and the trumpeter swan (*Olor buccinator*). The bald eagle and the falcon prey primarily on waterfowl; it is highly unlikely that the fires will have any effect on this prey base. However, the bald eagle does use fish to some extent (Swenson et al. 1986), and a serious fish kill from adverse runoff or sedimentation may affect nesting success. Trumpeter swans nest in riparian vegetation near the smaller lakes. Most of this vegetation is rhizomatous and will regenerate vigorously in burned areas. Thus nest cover and hence nesting success may actually increase for the swan.

Small mammals. Wood (1981) found that deer mice (*Peromyscus maniculatus*) and yellow-pine chipmunks (*Eutamias amoenus*) were more abundant in sites in Yellowstone Park that had burned two to five years previously than in unburned control sites. Although red-backed voles (*Clethrionomys gapperi*) were more abundant in unburned sites, it was the most common species in both. Shrews, (*Sorex cinereus* and *S. vagrans*) and montane voles (*Microtus montanus*) were found in both burned and unburned sites, but in numbers too small to make statistically valid comparisons.

Recovery of small mammal populations in burned areas will begin within one year. Initially, numbers of insectivorous and omnivorous small mammals should increase and numbers of herbivores should decrease in the burned areas, primarily because food resources for small mammals in these areas are predominantly insects and colonizing forbs (Wood 1981). However, there will probably be no losses of species, and total densities will be similar to those prior to the fire. Predators such as martens (*Martes americana*) and bobcats (*Lynx rufus*) will continue to have adequate prey. However, martens require thermal cover for resting in the winter, normally provided by older forests, and thus they may be negatively affected to some extent (Hagmeier 1956).

Large Mammal Populations. The indirect effects of the fires on large mammal habitats are much more important than the direct mortality caused by fires. The ability of fires to alter plant succession and affect the production and nutrient content of individual plants are reasons why wildlife species often respond favorably to habitats which have been burned.

Large mammal populations and their forage species in the Yellowstone region evolved in the presence of fire. Houston (1982) concluded that much of the vegetation change in the GYA rangelands resulted from fire suppression rather than grazing by ungulates. Increases in sagebrush, conifer invasion of grasslands, and deterioration of aspen stands were attributed to fire suppression. Prior to active suppression, fires would have burned across the northern winter ranges at 25-40 year intervals or more frequently, thereby rejuvenating the grasslands and aspen stands and eliminating the conifers. Fire suppression has been related to increases in woody species across the intermountain West (Gruell 1980).

The current policy regarding management of the large mammal species in the Park is predicated upon the hypothesis that they will be self regulating in a density-dependent fashion, based upon fluctuations in the available forage supplies (Cole 1971). When populations attain high densities relative to forage supplies, then the available nutrients for each individual diminish. This causes decreases in production and survival of young, and survival of older animals as well. Forage supplies fluctuate naturally every year, dependent upon precipitation patterns. The relationship between animal numbers, forage, and precipitation is highly dynamic and difficult to predict.

The effects of the 1988 fires on forage plants further complicate this relationship. Initially, bunchgrasses like Idaho fescue (*Festuca idahoensis*), an important forage species, may become less abundant, but probably will have higher tissue nutrient concentrations than unburned plants. At some interval, production probably will increase above pre-burn levels (Merrill et al. 1982, Blaisdell 1953). This pattern will vary among species, but the typical response of forage species to fire is an initial increase in nutrient content lasting for up to four years, and an increase in productivity for a longer period, depending upon species. If this pattern proves to be the major result of the fire, then large mammal populations should either not be affected or may increase. In addition, temporary increases in forage will result from decreased competition and shading from relatively nonpalatable shrubs and trees that were killed by the fires.

Approximately 10% of the Northern Range grassland/meadow areas were moderately to severely burned. Forested areas that provide shelter and some forage also burned. The primary consequences of these changes may be to alter animal distribution. As of January, over one third of the elk population has moved outside of the Park onto unburned ranges as a consequence of winter conditions being more harsh than in the recent past.

Experience elsewhere shows that factors other than winter range may control large mammal populations. In general, the effects of burning programs on population numbers have not been well correlated with habitat changes attributable to fire. Although fire improves forage supplies and large ungulates use the forage on burned areas preferentially to adjacent unburned areas, translating this to population changes rather than just distributional shifts is risky. For example, Bendell (1974) concluded that, although the moose population on the Kenai did increase after the fires of the late 1940's, there was no evidence to justify the assumption of cause and effect. Our understanding of the relationship of fire to elk habitat is no better.

Some important forage species (most especially big sagebrush) in the Yellowstone region do not resprout following fire. Conifers, such as Douglas-fir, that provide forage during critical winter periods when other plants are unavailable are often killed by fire. Additionally, grazing pressures may be sufficient in important areas that have been burned to preclude anticipated increases in production of the major forage species. If these factors are coupled with decreased production attributable to continuing drought, then the fires could contribute to a decline in large ungulate populations.

Thus, the effects of the fires on the large mammals in the Yellowstone region are of extreme interest from a management standpoint. Much of the controversy over the effects of grazing on the Park vegetation centers on woody plants, most especially aspen and willow. These species constitute a small but highly important part of the Park flora and it is assumed that their retention within the Park is an important goal. Both species resprout readily following fire and should produce vigorous shoots. Aspen stands which were in poor vigor prior to the fire may regenerate. Willow communities should also resprout rapidly. The fires of 1988 provide an opportunity to test the hypothesis that fire prevention is the main factor preventing aspen regeneration on the northern Yellowstone range, because many aspen stands were burned at various intensities. The influences of grazing pressure on regeneration of aspen and willow can and should be evaluated. The 1988 fires have provided a natural experiment with which to evaluate cause and effect relationships surrounding the status of willow and aspen as related to ungulate grazing and fire. Such observations may lead to reevaluation of the status of willow and aspen stands and the effects of current policy regarding elk, moose, and bison populations. Aspen stands are diminishing in number and vigor. If fire prevention has lead to this situation, then an important step towards perpetuating aspen inside the park will have been taken.

Although the availability of willow and sagebrush may be limiting food sources in a few locations, other forage species are generally more important. The bunchgrasses, sedges, and other palatable plants that are widely distributed provide the bulk of the elk and bison forage during dormant periods.

Original concepts of what constituted critical winter range for elk--the south facing slopes and ridgetops which become snow-free due to winter winds and sunshine--have largely been abandoned in favor of a winter range complex which includes other areas used during the winter period. Ungulate welfare depends on the condition of animals when they arrive on winter range. The better the animal's condition upon arrival on winter range, the higher the likelihood of the animal's survival and of reproducing. Improved forage conditions resulting from the fires on summer range will make the animal's survival on winter range better. Similarly, these summer and spring/fall ranges will be more productive in early spring when animals arrive from winter range, when the forage is needed to recoup energy losses incurred during the winter. The hypothesis that improved forage condition on spring-summer-fall ranges can compensate to some degree for inadequate winter range needs to be evaluated, and comparisons of ungulate population dynamics in areas which have been extensively burned with dynamics of ungulates occupying areas which have not been burned, or where burning is minimal, can help to evaluate this concept. Management implications for habitat improvement outside of this area are great, in that insight into seasonal ranges where forage improvement should occur may be obtained.

Ungulates will have to forage primarily on the unburned winter range areas this winter. None of the winter range outside the Park was burned. Elk began to move out of the Park onto adjacent National Forest winter range in November, and by mid-January, approximately one third of the Northern herd was outside the Park. Last winter, only a few moved beyond the Park boundaries. Much of what occurs during the 1988-89 winter will be related more to the drought than to the fires. Radiomarked elk living on both unburned and burned areas moved onto lower elevation ranges 3-4 weeks earlier this year than last, suggesting the that drought may be influencing their distributions more than the burns. None of these movements are unique or unanticipated.

Following the initial winter, shifts in distribution onto burned areas as soon as spring green up of forage species begins is anticipated. Changes in population attributes will be related to the post-fire forage conditions, the severity of the winter and drought, and prevailing weather conditions during the post-fire spring.

Observations on bighorn sheep response to fires (Peek et al. 1985) illustrate the range of variation that might be observed. Moose populations have been observed to disperse rapidly into a large burn in northeastern Minnesota and to be essentially unaffected by a large burn in central Alaska (Peek 1974, Gasaway and DuBois 1985). No significant information from moose range in the Yellowstone region on response to fire exists from which predictions can be made. Results from elsewhere are conflicting.

The opportunity to observe responses of a large mammal complex in such an extensive post-fire environment is unprecedented, and has implications for wildlife habitat management beyond the boundaries of the wilderness areas and the national park. Much habitat management for big game consists of the use of prescribed fire to increase forage production, and yet we have difficulty illustrating that populations respond other than by changing distribution patterns. The northern Yellowstone winter ranges that burned inside the Park constitute a significant portion of the winter habitat, and a much higher portion of the entire big game range in this region has been burned. An intensive monitoring program aimed at detecting population responses of each species which occupies burned areas, continued through time to account for delays and variation in other factors limiting populations, should be initiated to take advantage of this opportunity. The process should be allowed to proceed without human intervention as much as possible. The Yellowstone elk populations have served as bellwethers for management in the western states. They will surely continue to add to our knowledge because of the fires of 1988.

There will undoubtedly be strong pressure to feed big game--particularly elk--that reside in the north Yellowstone complex in this first winter after the 1988 fires. Such action seems unwise for the following reasons.

1. Ability to examine the relationships of ungulates to the post-fire environment will be compromised.

2. If, and we emphasize if, higher than average mortality is expected and that mortality is prevented by feeding, the result is apt to be an increasing population responding to enhanced postfire forage conditions on summer range. Such increases would put pressure on limited winter range, producing either higher mortality later on, or more likely, increased and continuing pressure for feeding programs.

3. The logistics of feeding this large elk population and the lesser numbers of mule deer, pronghorns, and buffalo on such short notice are extraordinarily difficult.

4. The chances of getting feed to all or even most animals where animals are not accustomed to being fed is small--i.e., such a program would have a low chance of being biologically effective.

5. Feeding large ungulates to maintain populations in excess of numbers that would exist otherwise is contrary to the current concept of maintenance of natural self-regulating populations which are not subject to hunting within the park boundaries.

6. The long-term problem for the northern Yellowstone elk herd is the paucity of suitable winter range where presence of large numbers of elk are acceptable. Concern and monetary resources generated by current conditions would be better diverted to a longer term solution--acquisition of suitable winter range outside the park--than to feeding programs.

Bears, both blacks and grizzlies, will also be influenced by the fires. The herbs and grasslike plants which provide most of their forage are not likely to be adversely affected by burning, but whitebark pine seeds which are important forage during some falls may be reduced in quantity. Estimates are that up to 20% of the communities containing whitebark pine inside Yellowstone were burned. Pine squirrels cache the seeds of this species in the ground and grizzly bears move primarily into the mixed conifer stands which contain whitebark pine, to exploit these seed caches. Whitebark pine seed crops are irregular, but when they are available they provide important forage for grizzly bears. Omnivorous species such as the grizzly adapt to changing availabilities of food sources, and other species such as clover, sweet cicely, and yampa serve as fall forages when pine seeds are not abundant. The effects of the fires on bears may be related to the abundance of fall forage species which determine the physical condition of bears as they enter hibernation and to the availability of food as they emerge from hibernation. Research on the responses of all known forage species to the fires, and into the food habits of bears on burned and unburned areas will be needed to thoroughly assess effects of fires on the bear populations.

Ungulates, both as prey and carrion, are fall forages for grizzlies. Prior to the hibernation period, concentrations of radio-collared grizzlies were located in areas where fires had burned rapidly and thoroughly, feeding on ungulate carrion attributable to the fires (D. Mattson, Grizzly Bear Study Team, pers. comm. to J. M. Peek, 8 Feb 89). These observations suggest that the bears are able to adapt to rapidly changing forage sources and are able to shift from one food item to another depending on availability. The abundance of ungulate carrion available to grizzlies in the spring as they emerge from dens and before green vegetation is available is also important in determining their survival and reproductive potential.

Part III. Research Needs and Opportunities

There are clearly many uncertainties regarding many of the specific ecological consequences of the 1988 fires. The course of many future events in Yellowstone will depend heavily on stochastic factors such as climatic variation which we have only limited capacity to control or predict. Thus forecasts must be phrased in terms of probabilities and possibilities. Our ignorance is not so much a matter of knowing the *range* of potential impacts of fire on ecological processes, but rather in understanding the interactions between site variables, vegetation, climate, and spatial scale that will produce a specific response. The heterogeneity and spatial scale of the 1988 fires have created a unique opportunity to address these issues.

The essential ingredients of a research program for events such as the GYA fires are (1) an ecosystem approach to provide for conceptual integration and operational coordination of many research projects, (2) a landscape or geographic context for individual projects, (3) provision for long-term studies and monitoring of key system characteristics and processes. The ecosystem approach will facilitate coordination of projects, which increases opportunity for serendipity and synergism, and the efficiency of investment in basic environmental monitoring (e.g., climate, streamflow) needed to support ecological and other studies. Understanding and recognizing the geographic context of research sites is necessary in order to extrapolate observations over larger areas based on information such as the burn severity maps. The 1988 fires will have ecological consequences that extend over a century or more. Therefore, it is important to set up research programs that deal with the long-term aspects of these processes through monitoring and other research efforts.

Specific Opportunities

Many research needs and opportunities were obvious to this panel during its deliberations, and these are described below. However, this list should not be viewed as complete or exhaustive. In developing a research program to deal with these issues it should be remembered that the Yellowstone fires are not unique in simply providing yet another place to study the ecological consequences of fire. Their uniqueness lies in their heterogeneity and scale, and in their significance to future wilderness fire management.

Fire Behavior and Management. Great progress has been made in the modeling of fire behavior, but the 1988 fires illustrated that much remains to be learned. Detailed daily records were kept and these, in conjunction with climatic data, can provide the basis for significantly improving the current understanding of fire behavior. The results will be relevant throughout much of the West and will provide the basis for fuel management programs when and where they are deemed necessary.

Research is needed on the desirability and technology of planned-ignition prescribed burning in GYA fuel types, especially lodgepole pine communities. Past experience seems to indicate that the range of fuel moisture conditions over which such fires might be carried out safely may be rather narrow. Certainly the potential environmental impacts of mechanisms for containing or confining such fires in heavy fuels must be thoroughly explored.

Fire History. Many current uncertainties regarding the interpretation of the 1988 fires result from limited information on the past fire history of the GYA. Excellent studies have been done, but it is still difficult to generalize to an area the size of Yellowstone National Park, much less the entire GYA. Furthermore, tree-ring studies have been able to extend the record back for only 200-300 years. Additional dendrochronological studies are needed, however, these should be planned so as to provide as complete a picture as possible of the history of *variability* in disturbance regimes across the GYA. Furthermore, these studies should be coordinated with palynological studies (using charcoal deposition in lake sediments) that can extend the fire history record back over millennia. The sediments created by the 1988 fires should be studied carefully, as they could be used to calibrate older sediment layers created by previous fires. Long-term data on fire frequency and extent should be compared to available paleoclimatic data, as well as information on past human activities, in order to refine our understanding of the factors that regulate fire behavior.

Considerable uncertainty exists regarding the role of fire management policies and patterns of human land use on fire behavior in the GYA in the period since the establishment of the Park and National Forests. Detailed historical studies coupled with studies of the behavior of simulation models of ignition and fire spread would certainly help resolve such uncertainties. Such studies would also facilitate many current theories regarding the relationships between landscape heterogeneity and natural disturbance.

Geomorphic and Hydrologic Processes. Available information will allow prediction of general hydrologic responses, but data on snowfall accumulation, rainfall, and other climatic conditions should be integrated with the terrestrial studies, so that the land-water interface can be examined over the wide variety of conditions created by the fires. The development of models of hydrological response to disturbances has depended in large part on comparison of paired watersheds. The extent, variety, and heterogeneity of the 1988 fires provides an unprecedented opportunity for a "gradient analysis" of watershed responses to the variety of disturbance impacts.

A history of patterns of fluvial and lacustrine sedimentation should be developed for representative watersheds in the GYA in connection with studies of fire history. Such a study would clarify relationships between watershed geomorphic processes and large-scale disturbance events.

Seeding with short-lived alien species is one of the most widely used postfire soil stabilization techniques and was used in several locations in the GYA. Studies should be undertaken to assess the effectiveness of this intervention. In addition, potential adverse impacts such as competition with native species and introduction of noxious weeds should be evaluated quantitatively.

Soils and Belowground Processes. Again, the heterogeneity of the 1988 fires provides ideal opportunities to understand the factors that contribute to range of potential effects of fire on soil processes. The soil mapping studies already underway will provide an excellent basis for such studies. Little is known regarding the relationship between variations in fire behavior and and soil characteristics that affect erosion such as hydrophobicity. Studies should be intiated to determine the impact of different fire intensities on such soil properties. The variability in fire behavior also provides unique opportunities to study the range of response of the soil microflora (including mycorrhizae) to variations in fire intensity.

Because nitrogen is so often limiting in GYA ecosystems, the dynamics of the cycling of this element deserve special attention. The responses of soil microorganisms, especially those related to nitrogen transformations, should be studied in relation to soil water chemistry. These studies should be coordinated with studies of streamwater chemistry.

Aquatic Ecosystems. The scale and heterogeneity of the 1988 fires provide unique opportunities to develop models of the relationships between physical, chemical, and biotic features of aquatic systems and patterns of disturbance. To do this, long-term monitoring should be intiated in streams of various sizes in major drainages. Specific studies should include an evaluation of ecosystem consequences of sediment and nutrient pulses in both fluvial and lentic systems. The role of fire in long-term nutrient cycling patterns in aquatic ecosystems should be determined. This may be particularly important in subalpine lakes where total productivity and carrying capacity for fish appear to have declined during the past century.

The role of landscape features such as riparian and wetland buffers in mitigating ecosystem responses deserves immediate attention. Studies to measure the extent to which such features alter streamwater chemistry or act as nutrient and sediment filters will provide an essential coupling of studies of aquatic and terrestrial ecosystems.

Successional Patterns. Studies of forest, shrubland, and meadow regeneration should be intiated as soon as possible. Although much is known of general patterns of successional change, the 1988 fires provide an unprecedented opportunity to relate patterns of response to such factors as topographic position, soil characteristics, burn intensity, preburn species composition, seed bank species composition, distance from unburned forest, and various characteristics of the burn mosaic. The management objectives of the Park permit long-term monitoring that might no be possible in adjacent National Forests. Furthermore, long-term studies already underway within the Park can serve as the basis for studies of successional change.

Frequent fires in the western Cordillera provide abundant opportunities to study postfire succession. To take advantage of the unique opportunities presented by the 1988 GYA fires, such studies must have a landscape focus; that is the opportunity to study successional consequences over spatial scales of meters to tens of kilometers must be exploited. It has been asserted frequently, with very little data, that large fires have important ecosystem consequences that are not similuated by frequent smaller burns. Future fire management plans will depend on tests of hypotheses related to this assertion and the 1988 fires provide unprecedented opportunities for such tests.

Biodiversity. The variety of habitats created by the 1988 fires will facilitate studies of recolonization rates of a variety of plant and animal species. Special attention should be payed to the potential effects of fire-caused habitat fragmentation on species populations and on changes in diversity on several spatial scales and along gradients of fire effects. Relatively few studies have been done on the impact of disturbances on genetic diversity. The GYA now provides an ideal laboratory for pursuit of long-term data on this topic.

The diversity and well-being of large mammals have been a persistent management and research focus in the GYA, and research in the wake of the 1988 fires will hopefully enrich or understanding of these animals even more. Alteration of food distribution and abundance will allow a timely test of assumptions regarding the role of forage supply in the regulation of numbers of ungulates. The potential impact of changes in populations of whitebark pine on populations of grizzly bear will require special study. Again, scale and heterogeneity of disturbance afford ideal opportunities to study the impact of disturbance mosaics on animal behavior.

The potential impacts of large mammals on other ecosystem properties and processes deserve special attention. For example, the relationship between ungulate populations and aspen population trends need study to determine whether documented declines in aspen are due to ungulate browsing, climate, fire suppression, or some combination of these factors. Furthermore, populations of ungulates should be monitored so as to determine their contribution to postfire changes stream sediment load. Because of their mobility, large mammals may have important effects of nutrient fluxes across the landscape.

Human Interactions. The 1988 fires provide opportunities to provide better data on the social and economic consequences of large-scale disturbances and fire management policy. Studies should be intiated to evaluate the impact of the fires on behavior and interests of Yellowstone visitors. Attention should be given to the time distribution of response with respect to the seasonality of visitor populations and the changes in observable characteristics of the burned environment. The publicity given to the 1988 fires has undoubtedly influenced predispositions and the level of understanding (or misunderstanding) of future visitors. Research on these influences may greatly improve the quality and value of interpretative programs. In relation to this issue, the impact of interpretive programs on visitor response should be objectively evaluated so that appropriate adjustments can be made.

The potential economic impacts of the 1988 fires attracted some concern on the part residents of tourism-dependent communities and on the part of political leaders concerned with policy options. Although such issues are not strictly within the realm of ecological impacts, it is clear that management and policy decisions in wilderness areas are conditioned by assumptions regarding their nonwilderness impacts. Carefully controlled studies of the pre- and post-fire economy of the GYA should be undertaken. Such an analysis should also include an evaluation of the costs and benefits of the suppression efforts associated with the 1988 fires.

Ecosystem Interactions. It should be obvious that the assignment of research needs and opportunities to specific categories is highly arbitrary. For example, studies of the impact of these fires on hydrologic and geomorphic processes, or the aquatic biota depend heavily on information on terrestrial ecosystem succession and animal behavior. Indeed, one of the most significant opportunities presented by this disturbance complex are studies at the land-water interface. An integrated ecosystem research program with a landscape perspective is clearly needed.

Initiating and Sustaining a Program of Ecosystem Research

Because of the location and scale of this event, tremendous public and scientific interest now centers on the GYA and several major research initiatives are already underway. The 1988 fires provide the opportunity to study disturbance at the landscape scale, in a landscape that has not been heavily influenced by humans, and in a context that should facilitate the establishment of long-term studies. The challenge is to focus these resources on important research issues and to organize a program that can follow through with long-term observations which are essential to interpreting the ecosystem consequences of the fires. In order to achieve this it is important to have substantial and rapid agency commitment.

There have been other instances of major disturbances in reasonably accessible, high-profile landscapes that have challenged land managers and researchers. The 1980 eruptions of Mount St. Helens, for example, created similar opportunities and challenges for ecosystem research. Certainly much has been learned there, but ecosystem research at Mount St. Helens has ebbed tremendously because agency commitment has been slow and insubstantial.

A coordinated ecosystem research program with both geographic and long-term perspectives can be developed for the GYA under a scenario involving large integrated groups supported by one or more major National Science Foundation grants, numerous smaller projects, and a core of scientific talent and facilities provided by Yellowstone National Park and the U.S. Forest Service, Rocky Mountain Research Station. Core support from the GYA agencies could be:

1. Have appropriate staffing at scientific and support levels to provide leadership for the larger scientific community involved in research in the GYA.

2. Foster communication and coordination among participating scientists and others who are considering working in the area. This can be done by organization and hosting of field-oriented conferences.

3. Promote research in the area of developing and making available facilities, such as wet laboratory space, to outside scientists.

4. Establish a data bank to archive, systematically document, and make available data from short-term and ongoing research, and monitoring activities. Such a data bank would be an invaluable a service to internal and external scientists.

5. Institutionalize a monitoring program for key ecosystem attributes, such as climate, selected animal species, and hydrology, and have the data flow directly and efficiently into the data bank. The components of this monitoring program should be selected so as to provide the data necessary to determine whether and to what extent management objectives are being met.

The payoffs from a broad-based analysis of ecosystem response to the 1988 fires in GYA will come to Yellowstone National Park and the National Forests of the GYA, to the Park and Forest Services in general, and to the scientific community at large. Wilderness managers have much to gain from strong ecosystem research programs focused on extraordinary events such as the 1988 fires.

Results of studies of the specific major events and other facets of ecosystem behavior are an essential basis for interpretative programs. Furthermore, management of many phases of the use of these areas, including providing for the health and safety of visitors, are tied to an understanding of ecosystem properties. Benefits to the agencies and the scientific community include development of a model for scientific response to major disturbances. Certainly large-scale disturbances of major scientific importance will occur in the near future. We have, as yet, no efficient approach to overcoming the fiscal, physical, social, and organizational hurdles to quick establishment of large-scale, multi-institution, ecosystem-oriented research programs.

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Appendix A

Interim Report

of the

Greater Yellowstone Postfire Ecological Assessment Workshop

Introduction

The workshop participants met on 19-20 November with the following objectives:

1. *Evaluate the apparent ecological impacts and implications of the 1988 fires as they relate to the areas of watersheds, fisheries, wildlife, forests, soils, ranges, and biological diversity.*

2. *Consider the short- and long-term need for reseeding areas for soil stabilization and erosion control.*

3. *Evaluate the need or desirability of a reforestation program in the parks, in wilderness areas, and in commercial forest stands.*

4. *In light of both the drought and fires of 1988, consider the need or desirability for supplementary feeding of ungulate species during the winter of 1988-1989.*

5. *Develop a list of short- and long-term postfire research needs.*

6. *Prepare a report summarizing the workshop proceedings.*

This interim report addresses objectives two, three, and four which we agreed required immediate attention. The broader objectives one and five will be addressed in our final report which will be made available no later than 1 February 1989. Our recommendations were arrived at after on-site reconnaissance, evaluation of available data and published literature relevant to our specific objectives, and considerable discussion during the workshop.

Objective Two: Seeding

Fire suppression activities within the Greater Yellowstone Area in 1988 involved caterpillar dozing of firelines (catlines) and helipads, as well as the cutting of firelines using hand tools. Furthermore, burned areas potentially susceptible to erosion have been identified. Should these human-disturbed and erosion-susceptible sites be seeded with short-lived alien species to stabilize soils and control erosion?

To date, catlines in National Forests bordering Yellowstone Park have been seeded with short-lived wheat and cereal rye. Catlines and trails within the park have not been seeded, but have had top soil (salvaged during line construction) moved back onto lines and covered with slash to minimize soil erosion and facilitate natural plant establishment.

Seeding may indeed stabilize soil surfaces and reduce soil erosion on a short-term basis, however, such activities may be harmful in the long term.

Non-native species often used for reclamation are potential competitors for native trees and shrubs, inhibiting establishment of many native plants. Thus, the introduction of such species can slow the natural process of plant succession which will ultimately control erosion over the long term. Planting of non-native plant species has actually been observed to accelerate erosion within a few years of fires in certain situations. Annual species often form dense root mats in the first year or two following establishment, but poor establishment in subsequent years (a likely scenario in high-elevation habitats) can create conditions favorable to mass slippage of surface soil layers bound together by such root mats.

The planting of commercial seed mixes will undoubtedly introduce annual and perennial weeds other than wheat and rye into wilderness ecosystems. Certainly, planting of alien species diminishes the pristine nature of the ecosystems into which they are introduced. We view the potential introduction of noxious weed species into park ecosystems as a serious threat if an extensive seeding program is undertaken.

The seeding activities done to date outside of the park may minimize short-term effects of severe suppression impacts, particularly on catlines cut on steep slopes. However, we recommend that areas where such seeding has been done be monitored carefully for signs of longer-term negative consequences. We recommend that no additional seeding of alien annual or perennial species be permitted, especially in designated wilderness areas and within the Park. Rehabilitation practices such as respreading topsoil and slash on catlines and hand lines within the park will facilitate the natural successional processes on these sites.

Objective Three: Reforestation

Given the severity and extent of the 1988 fires, would it not be prudent to reseed or plant seedlings of native trees and shrubs to accelerate natural successional processes to mature forests? Such activities might be especially appropriate in areas visited by particularly intense fires.

To date, reforestation activities have been confined to commmercial forest lands within the National Forest areas surrounding Yellowstone Park and to a few very localized sites within the Park near dwellings or along roads. Within the Park, care has been taken to collect seed for such activities from very near the planting site.

Postfire successional processes in the various forest, shrubland, and grassland ecosystems within the Greater Yellowstone Area have been extensively studied. In all cases it is clear that wildfire has been an integral ecosystem and landscape process for thousands, perhaps millions, of years. Nearly all native species in these ecosystems are adapted to fire in one way or another; indeed, a number of plant species depend on fires for successful reproduction. Adaptations include fire resistant bark, root systems that resprout following fire, serotinous cones that open and release their seeds following fire, and heat stimulated flowering and seed germination. The specific patterns of succession in these ecosystems will depend on a number of factors, including prefire ecosystem structure and species composition, local site environment, local patterns of fire severity, and postfire impacts such as year-to-year variations in climate. It is this combination of variables that was responsible for much of the landscape variability prior to the fires and will undoubtedly contribute to the heterogeneity of the future landscape of the Greater Yellowstone Area.

Fires of the magnitude and extent of those observed in the Greater Yellowstone Area in the summer of 1988 are relatively common in many western coniferous ecosystems and have been demonstrated to be an integral part of the Yellowstone landscape prior to the advent of European man. Indeed, much of the structure and heterogeneity of that landscape prior to this year's fires was a consequence of large fires in the early eighteenth century. Certainly, this is sufficient evidence that the natural successional processes are all that is necessary to regenerate the full range of forest ecosystems in the Greater Yellowstone Area. The goal in wilderness areas should be to preserve ecosystems and landscapes such that they appear and behave as they would in the absence of human interference. We should intervene in natural disturbance and successional processes only when necessary to protect life or property.

Reforestation activities will at best do little to accelerate regeneration of wilderness ecosystems and, at worst, may be quite detrimental. Activities associated with planting of seed and seedlings are likely to increase soil damage and erosion owing to trampling and mechanical activities. Furthermore, seeding in addition to the natural seed rain may result in overstocking (unnaturally high seedling densities) which can alter the course of forest succession. Much of the genotypic diversity of forest trees in western coniferous ecosystems has been shown to be related to small-scale variations in site conditions and past disturbance history. The obvious mosaic of site conditions created by the 1988 fires will undoubtedly select for a wide variety of genotypes among native species. There is no possible way in which artificial reseeding activities can duplicate this important selective process. The Yellowstone fires will provide an important laboratory in which to improve our understanding of the process of forest regeneration and the role of natural disturbance on landscapes. Interventions such as reforestation will severely compromise that research value.

We conclude that reforestation activities in the park and wilderness areas, such as seeding or planting of seedlings, are unnecessary given the natural regenerative potential of these ecosystems. Furthermore, such activities could have a variety of undesirable consequences. Succession may indeed be somewhat slower in areas where fires were especially severe; such variation in succession in relation to patterns of fire severity will contribute to future landscape heterogeneity and should be allowed to proceed with no human intervention. We recommend that no reforestation activities be attempted in Greater Yellowstone Wilderness areas. We recognize that such reforestation may be legislatively mandated and prudent in commercial forest areas. Reforestation activities in such areas should be reviewed by silviculturalists expert in postfire planting strategies.

Objective four: Artificial Feeding of Ungulates

Given the combination of drought and the 1988 fires, is it necessary or desirable to provide supplementary feed for ungulate species during the winter of 1988-89? Experience in Europe and in other locations in North America indicate that ungulate populations can be manipulated by artificial feeding. Such feeding programs have been instituted to prevent malnutrition loss, alter distribution patterns, and increase over-winter survival.

A primary purpose of the national parks and the national wilderness preservation system is to perpetuate and restore natural dynamic processes that operate among the flora, fauna, climate, and landscapes within. It follows that human interference with these processes must be minimal. The ungulates which occur in the Greater Yellowstone Area are part and product of the natural dynamic processes we seek to foster. They exert an influence on the vegetation and, in turn, are affected by their predators, the grizzly bear, black bear, cougar, coyote, and humans. They also help support the diversity of scavengers within the park, including eagles, ravens, magpies, bears, and coyotes.

Artificial feeding focuses on only one component of these ecosystems and ignores the others. The management objective for ungulates in the Yellowstone Wilderness does not include production of harvestable surpluses. Mortality through disease, malnutrition, predation, and accidents varies from year to year. Ungulates within the Park have exhibited increases over the past ten years, and decreases will also inevitably occur. These fluctuations may be obvious during some years and virtually unnoticeable in others, depending on winter severity, extent of drought, and other conditions. Attempts to prevent declines will inevitably exacerbate the situation in the long term. Indeed, feeding might actually have an adverse effect on elk herds by facilitating disease transmission.

The argument that the fires of 1988 were unique and therefore justify unusual activities such as winter feeding is very questionable. For example, less than 10% of the winter range of the northern herd was consumed by fire. Available evidence indicates that virtually all plant communities within this region originated from past fires. As indicated above, fires burn large areas of western coniferous forest each year and fires of this extent burned much of the Greater Yellowstone Area in the early eighteenth century. The elk populations have obviously coevolved over a long time with fire in this region, as elk have in many other areas within their range. We should make every effort to allow such evolution to continue without undue interference.

Supplemental feeding carried out in a one-time crash program is predicted to cost in excess of $2,000,000, with a low probability of success in terms of broad-scale effects. Such feeding would have to be initiated in early winter to provide for maximum effectiveness. Given that environmental impact statements must be prepared, appeals (if any) considered, and funds, feed, equipment, and personnel acquired to mount such an effort, it seems unlikely that the objectives could be met in time.

As with other forms of interference, a feeding program, regardless of its intent or success, would compromise ongoing research. The northern elk herd in Yellowstone has been the subject of a very long-term research effort; supplemental feeding--even for one year--would seriously complicate those studies by adding a variable the effects of which would be difficult, if not impossible, to assess.

Finally, one measure of our success in wildlife management consists of the degree to which we maintain wildlife populations independent of our influence. Aldo Leopold wrote that all wildlife exists at the discretion of mankind, implying that we exert indirect and direct influences over all living things on earth. Places where we must feed wildlife in order to sustain populations are places where we must settle for something less than what we have in Yellowstone.

Dynamic processes take avenues which may seem cruel and wasteful by some standards, but not from the standards of stewardship of natural ecosystems. The tendency to interfere is an understandable altruistic human response. However, in the case of our national parks and wilderness areas, this interference does not serve a useful purpose in the long-term scheme within which wildlife populations are being allowed to exist.

In summary, we recommend that feeding to mitigate the combined effects of drought and fire in the Yellowstone ecosystem should be rejected because: 1. it is contrary to the intent of management of the National Parks and the adjacent wilderness to maintain natural ecosystem processes; 2. it is unlikely to be effective and may produce effects opposite to those intended over the long term; (for example, it may enhance potential for disease transmission); 3. it is expensive to conduct; 4. it will confound long-term observations of elk responses to habitat.