ECOLOGY AND MANAGEMENT OF HIGH-INTENSITY FIRES IN YELLOWSTONE NATIONAL PARK

Don G. Despain
William H. Romme

INTRODUCTION

The 1988 forest fires in the greater Yellowstone area were sufficiently large and intense to attract the attention and concern of a worldwide audience. Numerous questions were generated concerning the influence of fire on ecosystem processes and the appropriateness of specific fire management practices. Wildland managers throughout the country now are faced with important decisions concerning the appropriate role and management of high-intensity fire in natural ecosystems (Philpot and Leonard 1988).

The principal management goal in Yellowstone National Park (YNP) is to maintain as natural an ecosystem as possible, and to eliminate or compensate for the influence of modern man (Houston 1971, Despain et al. 1987). Because high intensity fires are a natural part of the Yellowstone system, it follows that they should be allowed to play a role if possible. We need to understand more fully the ecological role of such infrequent but extensive and severe disturbances. Large, nearly pristine wilderness areas such as YNP are almost the only places where we can study these large fires without unduly threatening other lands where fire is unwanted. In this paper we first summarize our current knowledge about the high-intensity fire regime that characterizes the Yellowstone landscape, and then discuss some of the challenges and opportunities for fire management in YNP.

THE YELLOWSTONE FIRE REGIME

Our understanding of fire in the Yellowstone system is based on (i) analyses of changes in fuel conditions during forest succession, (ii) observations of uncontrolled fires from 1972-1988, and (iii) reconstructions of fire history since 1690. We briefly summarize each of these in turn.

Successional Changes in the Fuels Complex

Successional stage is an important determinant of fuel quantity and structure in subalpine forests dominated by lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) that cover most of YNP. The general successional sequence following stand-replacing fires (crown fires or severe surface fires that kill all or most of the above-ground vegetation) has been determined by sampling a chronosequence of stands burned at various times in the last 500 years (Despain in press).

For the first several years after a severe fire, the vegetation is dominated by herbaceous plants that resprout from surviving rootstocks and rhizomes or became established from seed (Lyon and Stickney 1976, Rowe 1983, Lyon 1984). Lodgepole pine seedlings also become established and begin to dominate the stand after one to two decades. This initial post-fire stage, designated LP0, continues until canopy closure, usually some 30-50 years after the fire. Dead woody fuel mass is very high, but it consists almost entirely of large dead tree boles that do not ignite readily. Very little fine woody fuel is available, and the herbaceous plants tend to remain green even during dry summers. The result is that the LP0 stage does not burn readily. Observations from 1972-1988 showed that fire may be carried by some of the large decomposing logs, but that fire intensity and rate of spread are typically very low.

After 30 to 50 years, the newly established cohort of lodgepole pine begins to form a closed canopy, marking the onset of the next successional stage, designated LP1. The trees usually are dense, and ground-layer vegetation is sparse. This stage extends throughout the period of intense competition and stand thinning, usually until about 150 to 200 years post-fire. Dead woody fuels on the forest floor consist of a compact layer of pine needles, the moldering remains of large tree boles killed in previous fire, and small dead stems of lodgepole pine trees that died from competition. In some stands, one or more of these dead woody fuel components may be substantial, but in most stands all three are low and most of the fuels present are live fuels in the canopy. A large discontinuity usually exists between dead woody fuels on the forest floor and the live fuels in the canopy. Like the LP0 stage, this stage of succession generally does not burn readily. Our observations have shown that fires will burn in these stands when strong winds drive flames into the tree crowns from a neighboring stand. However, when the wind stops the fire usually drops out of the canopy and may smoulder for a time in the sparse surface fuels before it finally goes out (Despain and Sellers 1977).

When tree growth, competition, and thinning are completed the stand enters the next successional stage, designated LP2. This stage is characterized by a more open structure and a denser, more diverse ground layer vegetation than the LP1 stage. An understory of lodgepole pine, Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) begins to develop. Dead woody fuel loads increase as mature canopy trees begin to die and fall, and grouse whortleberry (*Vaccinium scoparium* Leiberg) forms a nearly continuous ground cover in many stands. Observations show that these stands are still relatively fire-resistant under most conditions. The live fuels on the forest floor seldom dry sufficiently to burn, and understory fuels are not sufficient to carry a fire into the canopy (Van Wagner 1977). As with the LP1 stage, wind-driven fires can burn through LP2 stands. However, though the canopy is less dense than in the LP1 stage, it is still a closed canopy and attenuates the wind speed at the ground (Albini and Baughman 1979). Fires in LP2 tend to drop to the ground or go out when the wind stops, though localized patches containing a well developed understory or a large accumulation of fallen canopy trees will sustain a more intense fire.

When extensive mortality begins to occur in the canopy trees, and the developing understory trees reach two to three meters in height and begin to penetrate canopy gaps, the stand enters the LP3 stage. This final stage of succession is reached some 200 to 400 years after a stand-replacing fire. Fuels (in the form of dead tree boles, fallen branches, litter, and live crowns of understory trees) become abundant. Scattered pockets of deep organic matter are found on the forest floor where large trees are in final stages of decomposition; where needles have accumulated beneath large, old spruce or fir trees; and where squirrels have constructed large middens of cone scales. These localized accumulations of combustible material are important as sites where fire can start from a nearby lightning strike. They also are places where fires can persist during rainy periods, often flaring up again after days or weeks of quiescence when fuels again become dry enough to sustain a spreading fire.

In dry years when meteorological conditions are favorable for fires (more on this below), LP3 stands ignite readily and burn intensely. Understory trees can carry the flames from surface fuels into the overstory, generating crown fire (Van Wagner 1977). Wind can penetrate the opened canopy to the forest floor and produce very large fire fronts. The wind also may transport small burning twigs and particles one to two kilometers in advance of the fire, where they fall and ignite spot fires. LP3 stands support the most spectacular crown fires in YNP. They burn more continuously than any of the earlier successional stages, leaving fewer patches of unburned forest. Thousands of hectares can be burned in a few hours.

Observations of Uncontrolled Fires from 1972-1988

The natural fire management policy in effect in YNP from 1972 to 1988 permitted lightning-caused fires to burn without interference as long as they did not threaten human life, property, or other significant resources (NPS 1975). Detailed monitoring of 235 such fires that were allowed to burn between 1972 and 1987, as well as the extensive fires of 1988, provided an exceptional opportunity to learn about natural constraints on fire ignition, spread, and behavior. We first summarize our major conclusions about natural fire behavior from 1972-1987, when a wide range of fire sizes and intensities was observed, and then discuss some of the differences and similarities in fire behavior observed in the extreme weather of 1988.

Observations since 1972 have shown that the principal determinants of fire ignition and spread in YNP are weather conditions and the type and distribution of fuels. Lightning ignites fires every summer, but in most years the weather is so wet that the fires burn only a few hectares or less before they are extinguished naturally (Table 1). Only during five years from 1972-1988 were weather conditions dry enough to permit more than 100 ha to burn, and even in those years, many fire starts went out after a few days without spreading (this occurred early in the 1988 fire season as well). Most of the area that burned in the dry years of 1974, 1976, 1979, 1981, and 1987 did so during several key days when meteorological conditions were especially favorable for burning, i.e., when humidity was low and temperature and wind speeds were high (Despain in press, Renkin and Despain in prep.). Whenever fuel moisture was raised even by a light rain event the fires died down and remained inactive until the fuels became dry again. The large fires were not completely extinguished until snow came in late autumn; until then, high-intensity fire could flare up somewhere on the fire perimeter any time that weather conditions became suitable (Despain and Sellers 1977).

Fuel conditions in YNP are closely correlated with forest successional stage, as discussed above, and observations since 1972 have shown that the spatial distribution of successional stages has an important influence on the spread of fire across the landscape (Turner and Romme in press). Most fire starts have occurred in LP3 stands, and most of the area burned was in LP3 forests (Despain in press). Spreading, high-intensity fires have commonly been observed to burn up to the edge of LP2 or younger stands and to either stop or spot beyond the young stands to more distant LP3 stands, leaving only

Table 1. Area burned from 1972 to 1988 in Yellowstone National Park, Wyoming. Data from Diaz (1979) and courtesy of the U.S. National Park Service.

	Percent Mean Precipitation (1899-1977)			
Year	July	August	Number of fire starts	Area burned (ha)
1972	119	178	21	2
1973	106	126	33	59
1974	73	139	38	529
1975	141	67	26	2
1976	148	160	30	650
1977	195	163	29	27
1978	99	46	24	6
1979	115	151	55	4,548
1980	143	199	25	2
1981	103	25	64	8,338
1982	118	163	20	0
1983	269	88	7	0
1984	297	121	11	0
1985	160	84	53	13
1986	212	75	33	1
1987	303	122	35	390
Total (1972-1987)			503	14,566
1988	79	10	24	321,000

patches of burned duff and litter on the floor of the younger forest (Despain and Sellers 1977, Despain in press).

The fires in 1988 were orders of magnitude larger than any fires observed from 1972-1987 (Table 1). Why? The major reason apparently was the unusually prolonged period of weather conditions suitable for fire spread (Romme and Despain 1989a,b,c). The number of fire starts was about average, but summer precipitation was far below normal (Table 1). There was essentially no rain for several weeks, during which time fuel moisture in large diameter fuels fell to under 10%. These dry conditions, combined with high winds, created a situation in which high-intensity fires could spread over large areas. The most important difference between fire behavior in 1988 and in 1972-1987 appears to have been the duration of extreme fire behavior; fires in 1981, for example, actually burned with nearly the same intensity and rate of spread as fires in 1988, but the duration of the requisite dry, windy weather conditions was far less in 1981. Because of the unusually dry fuel conditions and the persistent wind in 1988, early forest successional stages burned more readily than they had in earlier years; nevertheless, there still was a disproportionate area of older successional stages burned in 1988 (Renkin and Despain, in prep.).

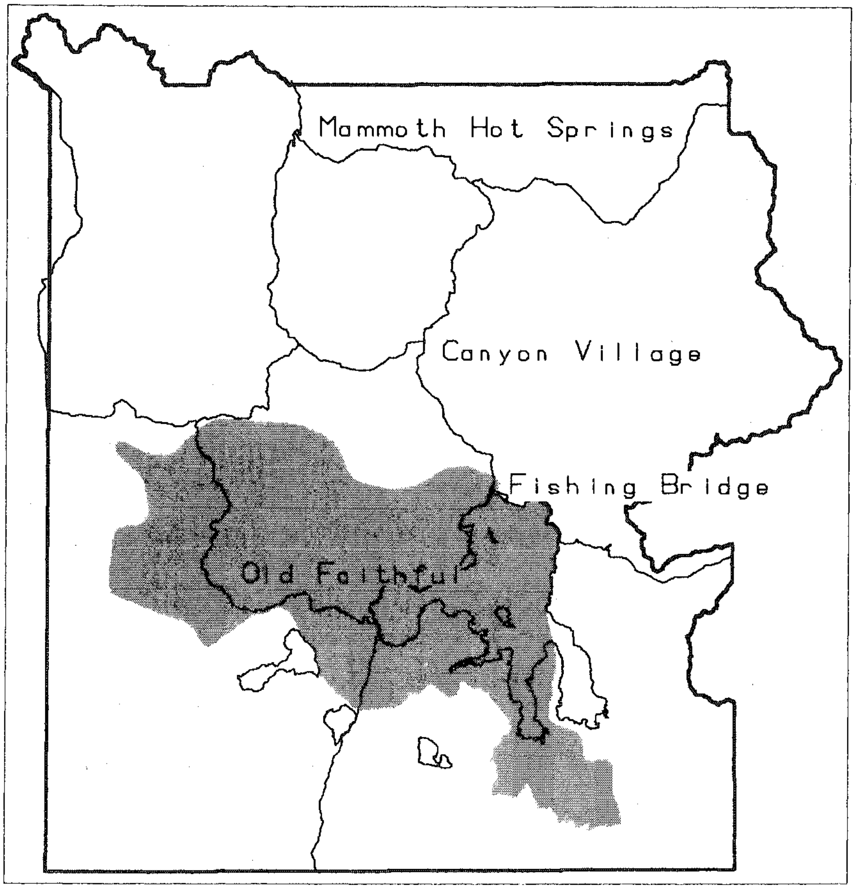
Yellowstone's Fire History

Large high-intensity fires evidently have been a part of the Yellowstone landscape for a very long time. An aerial view of the forests that cover approximately 80% of the park shows large patches of even-aged lodgepole pine forest that developed following ancient fires. Fires that burned as much as 400 years ago are still evidenced by an even-aged lodgepole pine overstory. Charcoal in lake and pond sediments and in alluvial and colluvial deposits indicates the occurrence of fires throughout the Holocene (C. Barnowsky, pers. comm.; S. Wells, pers. comm.).

Fire history at the lower forest border in northern YNP was investigated by Houston (1973), who found that fires had recurred at intervals of 20-25 years prior to the twentieth century. The tree-ring data from fire-scarred trees also suggested that eight to ten extensive fires had occurred in the area in the last 300-400 years. Houston's results indicated that the fire regime at lower elevations in YNP, near the forest-grassland border, was characterized by relatively frequent fires, as has been reported for other areas in the northern Rocky Mountains (Arno 1980).

Most of YNP lies at higher elevations, however, where the climate is cooler and wetter than in Houston's study area and where the vegetation is dominated by closed coniferous forests. We reconstructed fire history in a 129,600-hectare study area in south-central YNP that appears representative of the high-elevation volcanic plateaus that cover most of the Park (Fig. 1). Aerial photos (1:20,000 scale) were used to produce a preliminary map of homogeneous-appearing patches, and then one or more stands within each patch were

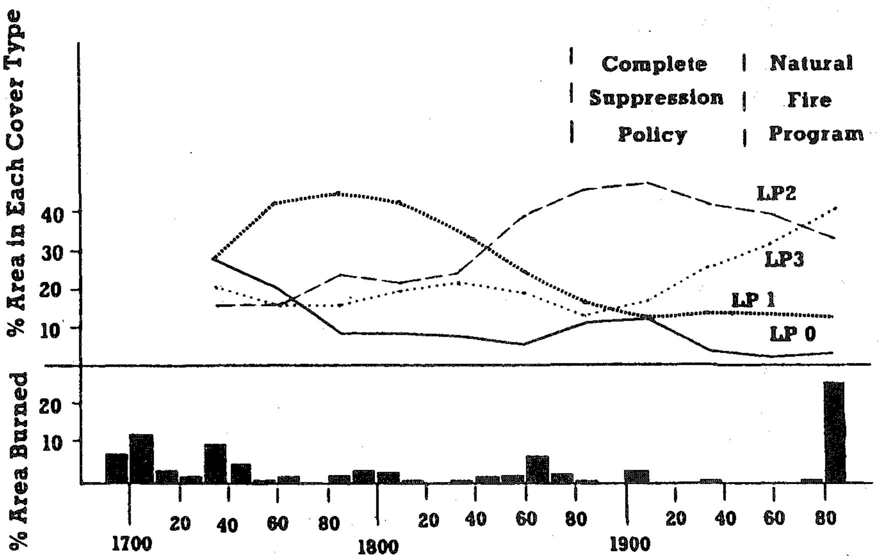
Figure 1. Fire history study area on volcanic plateaus of Yellowstone National Park.



sampled. Age of each stand was determined by sampling fire-scarred trees that could sometimes be found around the edges of a patch (Arno and Sneck 1977). We also cored several dominant trees that apparently germinated after the last stand-replacing fire. Where no scarred trees could be found, the age of the stand dominants was used to approximate the year of the last fire. Finally, the area burned by each major fire in the last 300 years was mapped by use of field notes and 1:20,000 scale aerial photography. The fire history data also were combined with our knowledge of rates and patterns of post-fire succession to reconstruct the mosaics of successional stages that probably covered the landscape at various times in the last 250 years (for details of methodology see Romme 1982, Romme and Despain 1989a,b).

Fires were found to have occurred in every decade since 1690 (Fig. 2). However, in most decades the fires burned only a small area. Major fire events occurred in just four key periods: 1690-1710 (when 19% of the study area

Figure 2. Top: Percent of the forests within the study area covered by each successional stage from 1735 through 1985. The reconstruction extends back only to 1735 because extensive fires around 1700 destroyed the evidence necessary to reconstruct earlier landscape mosaics. Bottom: Percent of study area covered by stand-replacing fires in each decade from 1690 to 1988.



burned), 1730-1750 (15% burned), 1860-1870 (7%), and 1988 (26%). The extensive areas that burned in the early 1700s then passed through early successional stages (LP0, LP1, and LP2) throughout the remainder of the 1700s, through the 1800s, and into the early 1900s (Fig.2). The generally small extent of fires during that period (mid-1700s to early 1900s) may be due in part to the predominance of these relatively nonflammable successional stages across the landscape. Lightning probably ignited fires every summer, just as it does today, but it was not until the mid-twentieth century that highly flammable LP3 forests were again dominant and connected across the landscape. The vegetation and fuels complex probably could have supported extensive, high-intensity fires any time after about 1930, but it was not until 1988 that a summer occurred with the prolonged drought and wind that are also necessary for extensive fires in YNP.

Twentieth-century fire suppression apparently had only a minor influence on vegetation structure and dynamics on Yellowstone's subalpine plateaus (Romme and Despain 1989 a,b,c; cf. Cooper 1960, Dodge 1972). Suppression probably was not very effective in the early years because much of the area was remote and inaccessible. Technologies for detecting and suppressing fires were greatly improved in the 1940s, after which time fire control efforts undoubtedly reduced the size of many fires (though our experience with uncontrolled fires since 1972 suggests that many of the "suppressed" fire starts would have been extinguished naturally even without suppression, because of wet conditions). Thus, the period of consistent fire control in Yellowstone actually was from the mid-1940s into the early 1970s when the Park's natural fire management program was initiated.

It seems unlikely that this 30-year period of fire suppression had any major effect on overall fuel conditions in YNP or on the behavior of fires in 1988. A highly flammable fuel complex develops slowly over a period of 200-300 years within individual stands (Romme 1982), and an extra 30 years without fire is likely to produce only small changes in fuel loads in most stands. Moreover, there is not a monotonic increase in all fuels categories over time. Rather, various components of the fuels complex change differentially over time, and some (e.g., fine fuels) actually appear to decrease slowly after stands reach 200 years in age (Figures 3-6 in Romme 1982). The most important change in flammability appears to take place with the transition from LP2 to LP3, which occurs over a period of decades. Thus, 30 years of fire suppression probably had only a small effect on fuels dynamics within individual stands.

It is true, however, that the total area covered by LP3 forests increased substantially between 1945 and 1975 (Figure 2). The resulting increase in area and continuity of highly flammable forests probably contributed to the size and intensity of the 1988 fires. But was fire suppression the major reason for this change in fuel conditions across the Yellowstone landscape? We think not. The most important cause of the increase in LP3 was the extensive fires of the early 1700s (Figure 2), which had initiated a more-or-less synchronous wave of succession over a large area of the Park. All of these stands were at the appropriate age to undergo transition from LP2 to LP3 in the mid- to late 20th century. There would have been a large increase in the extent of LP3 between 1945 and 1975 regardless of what fire management program had been in effect, unless that program entailed the burning of thousands of hectares every year.

Would thousands of hectares have burned every year in the absence of fire suppression? Probably not. Most summers in YNP are too wet for fires to spread over large areas (Renkin and Despain, in prep.). Examination of the fire records indicates that there were only seven years within this period when weather conditions were dry enough to require major firefighting efforts: 1946, 1949, 1953, 1960, 1961, 1972, and 1974. We will never know how large those fires might have become had they not been suppressed. However, at least some of the fires (e.g., in 1949) were partially extinguished by heavy rain storms before firefighting crews arrived (YNP fire records), and probably would not have grown much larger even if left alone. Moreover, none of those years had the extreme weather conditions of 1988; if they had, then fire control probably would have been no more effective in those earlier years than it was in 1988.

We conclude, therefore, that fire behavior in 1988, though spectacular, nevertheless was probably not greatly different from the behavior of the comparably large fires that burned in the early eighteenth century (Romme and Despain 1989a,b,c).

In summary, our analyses of successional changes in the fuels complex, observations of uncontrolled fires since 1972, and reconstructions of fire history lead us to conclude that high-intensity fire is ecologically the most important type of fire in Yellowstone's subalpine forests. It occurs in nearly every stand before succession progresses to the theoretical climax stage of an Engelmann spruce-subalpine fir forest; indeed, such "climax" stands are rare in YNP. Lower-intensity fires do occur; they may creep through the understory or forest floor and kill a few overstory trees, but these fires rarely cover large areas and appear to have far less ecological effect than the high-intensity fires. Extensive, high-intensity fires occur infrequently in Yellowstone because most summers are too wet, but in unusually dry years high-intensity fires can burn very large areas, as occurred in 1988. In fact, most of the area burned in YNP is burned by only a small number of rare but very extensive fires; these fires create a new mosaic of forest successional stages that then dominates the landscape until the next extensive, high-intensity fires (also see Heinselman 1973, 1981; Hemstrom and Franklin 1982; Johnson and Fryer 1987, Baker 1989a,b,; Turner and Romme in press).

MANAGEMENT CHALLENGES AND OPPORTUNITIES

The natural fire regime that characterizes Yellowstone's subalpine landscape is perhaps the most difficult kind of fire regime to manage. The extensive fires of 1988 have been likened to volcanic eruptions, hurricanes, and other uncontrollable natural disturbances. There is an important difference, however, in that we can control most of the fires in YNP; the truly uncontrollable fires come along only every century or so. Yet the way in which we manage the smaller, controllable fires ultimately may influence the behavior of the rare uncontrollable fires, as well as the overall wilderness character of the Park. Therefore, we examine the opportunities and challenges presented by a range of plausible options for fire management in YNP: (i) eliminating all fires; (ii) suppressing all unplanned fires, whether ignited by lightning or humans, and simulating natural fires with manager-ignited prescribed fires; and (iii) allowing some lightning-ignited fires to burn without interference under prescribed conditions.

The first option, total fire suppression, is necessary in most of our forested lands today because of human values at risk. In large wilderness areas like YNP, however, total fire exclusion is inconsistent with established goals of maintaining an ecosystem shaped primarily by natural processes (Houston 1971, NPS 1975). In time such a policy, if effective, would impoverish the biological diversity of the area (Taylor 1973, Romme 1982), and suppression techniques themselves may cause long-lasting changes in soil and vegetation structure, especially when heavy equipment is used. Furthermore, in any vegetation where flammability increases with plant succession, total exclusion of fire will inexorably increase the area and continuity of highly flammable forests, leading eventually to large, potentially uncontrollable fires (cf. Minnich 1983). For these reasons, a policy of total fire suppression appears both inappropriate and unmanagable in YNP over the long term (also see Philpot and Leonard 1988).

A policy of suppressing all unplanned ignitions and simulating the natural fire regime with manager-ignited prescribed fires is feasible, but difficult for both technical and philosophical reasons (also see Schullery 1989, Schullery and Despain 1989). First, the kinds of prescribed fires with which managers have most experience and expertise are low-intensity surface fires. As explained above, these kinds of fires appear to be relatively unimportant in Yellowstone's high-elevation forests. If manager-ignited fires are to be used to simulate the ecologically significant natural fires, then they should be high-intensity crown fires. Such fires are possible only during dry weather conditions, however, when there is a high risk of the fire escaping control and burning a larger area than desired.

A philosophical difficulty with manager-ignited prescribed fires as a substitute for natural fires in YNP is that our present knowledge of the natural fire regime is inadequate to provide the necessary base for designing a suitable burning schedule that would mimic all of the important features of natural fires. For example, a striking feature of the 1988 fires was their heterogeneity. The intricate patterning of severely burned, lightly burned, and unburned patches within the overall fire perimeters could not have been predicted on the basis of our pre-1988 fire experience. The details of this spatial patterning of fire effects across the Yellowstone landscape have important implications for plant succession, wildlife habitat, terrestrial-aquatic linkages, and individualistic species responses (e.g., Romme and Knight 1982, Christensen et al. 1989, Knight and Wallace 1989, Minshall et al. 1989, Singer and Schullery 1989, Turner and Romme in press). The ecological implications of fire scale and heterogeneity are only partly understood at present, but the essentially natural burning patterns of the 1988 fires have created an unprecedented opportunity for scientific investigation of these and other aspects of large-scale disturbances in the Yellowstone landscape.

The third option, that of allowing lightning-caused fires to burn without interference under certain conditions, is a central part of the current fire management plan in YNP (NPS 1975). This option is most consistent with overall Park goals (Houston 1971), and was widely regarded as a great success from 1972-1987. Though it received some severe criticism in 1988 (e.g., Buck 1989), the coincidence in that year of prolonged drought, wind, multiple ignitions, and a forest landscape in its most flammable stage, makes it doubtful that any conceivable fire policy would have led to a substantially different outcome.

This point is worth examining further, for some have suggested that the Yellowstone fires would have been much smaller if Park managers had more aggressively attacked all fires early in the 1988 season. We can never know for certain what would have happened if other actions had been taken, of course, but it seems unlikely that earlier suppression would have made much difference. More than 95% of the total area burned in the Greater Yellowstone area burned after July 21, the day on which suppression was ordered on all fires, regardless of origin. Three human-caused fires, which were suppressed from the outset, burned hundreds of thousands of acres despite the best efforts of well-equipped and well-trained fire fighters. Lightning also ignited several fires during those same extreme conditions, but the lightning-caused fires soon spread into fires that were already burning. Given the burning conditions of 1988, it is highly probable that roughly the same area would have been burned even if total suppression had been applied from the beginning to every fire that started in the greater Yellowstone area.

Thus, one of the main lessons of 1988 seems to be that extensive, high-intensity fires are an infrequent, but ultimately unavoidable element in whatever fire management option we choose in YNP. The federal fire management policy review team, appointed following the 1988 fires, concluded that a natural fire management policy like that in YNP was sound, though it recommended some further evaluation of the policy's implementation (Philpot and Leonard 1988).

Large wilderness areas such as YNP are the only remaining places where this kind of a natural fire management policy is still possible. Yet, even in Yellowstone's 880,000 ha, implementation of this policy is not without challenges.

The biota are well adapted to periodic high-intensity fires, but some resources may be damaged, such as archaeological artifacts and the historical record contained within tree-rings. Allowing certain fires to burn without interference also puts managers at great risk of criticism on those few occasions when the fires grow to such a size that they cannot be controlled. Similarly, some fires that are within the burning prescription initially may require suppression later when they become large or spread in unacceptable directions. This substantially increases the cost of suppression. Moreover, when suppression becomes necessary, managers must choose which techniques are to be used; generally they select techniques that minimize undesirable impacts on soils and vegetation, but this leaves them open to further criticism if the suppression effort is not successful.

CONCLUSIONS

The natural fire regime in the subalpine forests of YNP is characterized by infrequent but extensive, high-intensity fires. Lightning ignites fires every summer, but wet weather conditions preclude large fires in most years. Only in dry summers do fires burn more than a few hundred hectares, and probably only every 100-300 years do fires occur of the magnitude witnessed in 1988.

Our experience with uncontrolled fires since 1972 has yielded some unexpected insights into the opportunities and challenges of managing such a fire regime within the context of a natural ecosystem. On the one hand, many of the fires that were formerly "controlled" probably would have gone out by themselves without any intervention. On the other hand, there are situations in which fires cannot be controlled by any currently available means. When fires start under the kinds of extreme burning conditions observed in late August and early September of 1988, they can develop into uncontrollable fires regardless of suppression efforts.

In acknowledging the central ecological role of fire in shaping the Yellowstone landscape, and in allowing high-intensity fires to continue playing that historic role, both managers and the public need to recognize that there is always the risk that some fires will burn a larger area than desired. However, in the long run, some large fires probably are unavoidable in this type of ecosystem. Furthermore, as long as all fires are automatically suppressed, we cannot know how effective our suppression efforts really are. We need large wilderness areas like Yellowstone, where high-intensity fires and other primeval forces can be allowed to continue playing their natural roles, so that we may better understand the basic ecological processes that have shaped the biosphere.

ACKNOWLEDGMENTS

The fire history research reported here was supported by the National Science Foundation, grant number BSR-8408181, and the University of Wyoming-National Park Service Research Center. Support for writing this paper was provided in part by the Ecological Research Division, Office of Health and Environmental Research, U.S. Department of Energy, under contract number DE-ACO5-840R21400 with Martin Marietta Energy Systems. We thank Monica Turner, John Varley, and Paul Schullery for critical reviews of the manuscript.

LITERATURE CITED

Albini, F. A. and R. G. Baughman. 1979. Estimating wind speeds for predicting wildland fire behavior. USDA Forest Service, Research Paper INT-221. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Arno, S. F. 1980. Forest fire history in the northern Rockies. Journal of Forestry 78:460-465.

Arno, S. F. and K. M. Sneck. 1977. A method for determining fire history in coniferous forests of the mountain west. USDA Forest Service General Technical Report INT-42.

Baker, W. L. 1989a. Landscape ecology and nature reserve design in the Boundary Waters Canoe Area, Minnesota. Ecology 70:23-35.

Baker, W. L. 1989b. Effect of scale and spatial heterogeneity on fire-interval distributions. Canadian Journal of Forest Research 19:700-706.

Buck, B. 1989. A Yellowstone critique, something did go wrong. Journal of Forestry 1989(Dec.):38-40.

Christensen, N. L., J. K. Agee, P. F. Brussard, J. Hughes, D. H. Knight, G. W. Minshall, J. M. Peek, S. J. Pyne, F. J. Swanson, J. W. Thomas, S. Wells, S. E. Williams, and H. A. Wright. 1989. Interpreting the Yellowstone fires of 1988. BioScience 39:678-685.

Cooper, C. F. 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. Ecological Monographs 30:129-164.

Despain, D. G. In press. Yellowstone vegetation: Consequences of environment and history. Roberts Rinehart.

Despain, D. G. and R. E. Sellers. 1977. Natural fire in Yellowstone National Park. Western Wildlands 4:20-24.

Despain, D. G., D. Houston, M. Meagher, and P. Schullery. 1987. Wildlife in transition. Roberts Rinehart.

Diaz, H. F. 1979. Ninety-one years of weather records at Yellowstone National Park, Wyoming, 1887-1977. National Oceanic and Atmospheric Administration, Environmental Data and Information Service, National Climatic Center, Asheville, North Carolina.

Dodge, M. 1972. Forest fuel accumulation—a growing problem. Science 177:139-142.

Heinselman, M. L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quaternary Research 3:329-382.

Heinselman, M. L. 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. Pages 7-57 *in* Mooney, H. A., T. M. Bonnicksen, N. L. Christensen, J. E. Lotan, and W. A. Reiners, eds. Proceedings of the conference on fire regimes and ecosystem properties. USDA Forest Service General Technical Report WO-26.

Hemstrom, M. A. and J. F. Franklin. 1982. Fire and other disturbances of the forests in Mount Rainier National Park. Quaternary Research 18:32-51.

Houston, D. B. 1971. Ecosystems of national parks. Science 172:648-651.

Houston, D. B. 1973. Wildfires in northern Yellowstone National Park. Ecology 54:1111-1117.

Johnson, E. A. and G. I. Fryer. 1987. Historical vegetation change in the Kananaskis Valley, Canadian Rockies. Canadian Journal of Botany 65:853-858.

Knight, D. H. and L. L. Wallace. 1989. The Yellowstone fires: Issues in landscape ecology. BioScience 39:700-706.

Lyon, L. J. 1984. The Sleeping Child burn—21 years of postfire change. USDA Forest Service Research Paper INT-330.

Lyon, L. J. and P. F. Stickney. 1976. Early vegetal succession following large northern Rocky Mountain wildfires. Pages 355-375 *in* Proceedings of the Fourteenth Tall Timbers Fire Ecology Conference and Fire and Land Management Symposium. Tall Timbers Research Station, Tallahassee, Florida.

Minnich, R. A. 1983. Fire mosaics in southern California and northern Baja California. Science 219:1287-1294.

Minshall, G. W., J. T. Brock, and J. D. Varley. 1989. Wildfires and Yellowstone's stream ecosystems. BioScience 39:707-715.

NPS (National Park Service). 1975. The natural role of fire: A fire management plan for Yellowstone National Park. Unpublished report, Yellowstone National Park.

Philpot, C. and B. Leonard. 1988. Recommendations of the fire management policy review team. Federal Register (December 20, 1988) 53(244):51196-51203.

Renkin, R. and D.G. Despain. In preparation. Occurrence and activity of lightning-caused fires relative to weather and forest type in Yellowstone National Park.

Romme, W. H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecological Monographs 52:199-221.

Romme, W. H. and D. G. Despain. 1989a. The long history of fire in the Greater Yellowstone ecosystem. Western Wildlands 15:10-17.

Romme, W. H. and D. G. Despain. 1989b. Historical perspective on the Yellowstone fires of 1988. BioScience 39:695-699.

Romme, W. H. and D. G. Despain 1989c. The Yellowstone fires. Scientific American 261:36-46.

Romme, W. H. and D. H. Knight. 1982. Landscape diversity: The concept applied to Yellowstone Park. BioScience 32:664-670.

Rowe, J. S. 1983. Concepts of fire effects on plant species and individuals. Pages 135-154 *in* R. W. Wein and D. A. MacLean, eds. The role of fire in northern circumpolar ecosystems. SCOPE 18, Wiley.

Schullery, P. 1989. The fires and fire policy. BioScience 39:686-694.

Schullery, P. and D.G. Despain. 1989. Prescribed burning in Yellowstone National Park: A doubtful proposition. Western Wildlands 15:30-34.

Singer, F.J., and P. Schullery. 1989. Yellowstone wildlife: Populations in process. Western Wildlands 15:18-22.

Taylor, D. L. 1973. Some ecological implications of fire control in Yellowstone National Park. Ecology 54:1394-1396.

Turner, M. G. and W. H. Romme. In press. Landscape dynamics in crown fire ecosystems. In R. D. Laven and P.N. Omi, eds. Pattern and process in crown fire ecosystems. Princeton University Press.

Van Wagner, C. E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7:23-34.