# Chapter 3

***Using Yellowstone's Past to Understand the Future***

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Wildfire is universally understood to be a critical process in most forested ecosystems. Ecologically, it is as important as water, soil, and sun. Today, in the Greater Yellowstone Ecosystem and across the West, policy makers are calling for information about how vegetation and natural disturbances, like fire, will be altered by current and projected climate change. Cathy Whitlock, through her study of ancient pollen, charcoal and other fossils preserved in the sediments of lakes and wetlands, is gaining new insights about climate's role in long-term ecosystem dynamics. Collaborating with ecologists, archeologists, and climate change specialists, she seeks to better understand the role of climate and humans in shaping past plant communities and fire activity. A significant finding of Whitlock's work is that ecosystems respond to climate variations that occur over a wide range of spatial and temporal scales, including year-to-year weather conditions conducive to fire, decadal droughts that cause tree mortality and fuel build up, and long-term climate changes that shape plant communities and fire regimes. Understanding climate change in its many expressions is an important part of planning and adapting to modern and future conditions. Whitlock's work provides useful insights for resource managers as they grapple with the question of how to provide stewardship to our public lands in the face of future climate changes.

*J. Johnson*



The Runoff at Cutoff Creek (Trey Ratcliff)

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# Using Yellowstone's Past to Understand the Future

***Cathy Whitlock***

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*Yellowstone's spectacular scenery is the outcome of cataclysmic volcanism, the waxing and waning of large glaciers, and carving the landscape by mighty rivers. The forest and grasslands that blanket the region are a relatively recent addition to the Park, forming about 15,000 years ago on the heels of the last ice age, but they too have been shaped by past geologic events.*

Given its dynamic setting, Yellowstone is a wonderful playground for someone who thinks about environmental history, as well as an area of special concern when contemplating the impact of current and future threats. Questions about the natural resilience of the biota to environmental surprises such as wildfire or drought, the rate at which plant communities are capable of forming and dissolving, and the sensitivity of species to changing climate conditions are as relevant for understanding the past as they are for the future. Gaining knowledge about the history of vegetation, fire, and climate is part of the science of paleoecology - the study of past interactions between plants, animals and the physical world. Paleoecologic insights about long-term ecosystem dynamics have been central in the discussions that underlie important management decisions in the Yellowstone region, and they are proving pivotal as we confront current and projected climate changes and other human-induced threats.

This chapter provides an overview of paleoecologic research in the Park over the last three decades. I begin by describing how a paleoecologist "sees" a place like Yellowstone and formulates research questions that motivate field and laboratory work. Some of the significant findings on Yellowstone's history are discussed next, including the role of geology and climate change and the importance of past fires in shaping the ecosystem. Finally, I discuss why knowledge of the past has become an essential part of evaluating the current and future status of the Yellowstone region.

## *What Do We Do and Why Do We Do It?*

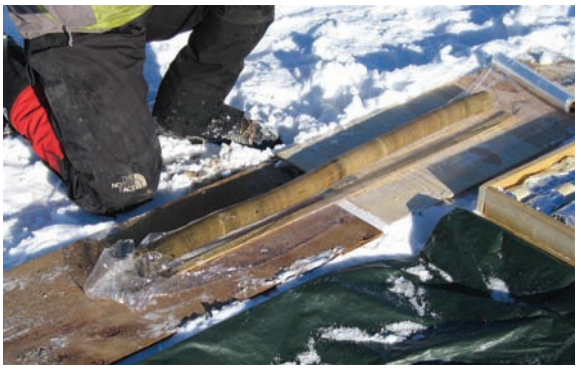
Historical sciences, like paleoecology, often answer questions through an iterative testing of multiple working hypotheses. Plausible hypotheses (explanations) are formulated at the outset of the study, and data are used to evaluate the merits of each hypothesis and reject those that don't hold up to scrutiny. Some of the hypotheses are rejected outright, others are modified in light of new discoveries, and new hypotheses emerge during the course of the investigation. In the case of Yellowstone, our research and testable hypotheses have focused on how ancient organisms individuals, populations, and communities responded to changes in the natural ecosystem of the past. The idea is that understanding past associations and interactions provides insight into the present and the future. We are also interested in understanding the hierarchy of climatic and nonclimatic drivers that have shaped the environment while recognizing that these drivers operate at a variety of scales, ranging from continent-wide, slowly-varying changes in climate to local and abrupt disturbances that briefly affect individual watersheds. Another issue of interest has been the role of geology in shaping the history and current distribution of vegetation. Is the dynamic geology of glaciers, earthquakes or geological structure a more important driver of vegetation change, for example, than climate or biological interactions? Finally, does location within the Yellowstone region affect the sensitivity of vegetation to environmental change, and if so, what does this bode for the future?

Natural lakes and wetlands are the best source of information on the history of terrestrial environments. Pollen, charcoal and other fossils preserved in the layers of sediment provide a script of changes that have occurred in the watershed over thousands of years. These layers can be recovered by removing cores from the sediments. The history begins with the deepest layers,

deposited when the lake was first formed, and ends with the top layer deposited in the current year. Most of Yellowstone's lakes were created during the final melting of the Yellowstone ice cap, about 15,000 years ago. In the intervening millennia, most lakes have deposited layers of sediment up to eight meters thick. In choosing which lake to sample, we consider its location and how representative the local vegetation, geological substrate, and climate are of a particular region. We are hoping to capture the range of environmental and biotic diversity that exists in Yellowstone.

To study the layers of history, sediment cores are collected, and their fossils and other constituents are examined. A variety of hand-operated coring equipment is available for this purpose, and the selection of an appropriate device depends on the study question and the historical time span needed to answer that question. Information about recent environmental changes, for example, can be found in the upper meter of sediments at most sites. These are recovered in a simple tube fitted with a piston lowered into the sediment. Another version is a meter-high metal box is filled with dry ice. The ice is dropped down the box, the sediments freeze to the outside and samples are recovered. Research concerning the entire 15,000 years of history requires more complicated coring equipment, including a square-rod piston corer attached to metal drive rods. This device takes cores that by five centimeters and one meter long in vertical succession. Each drive is brought to the surface, and the sediments are extruded and wrapped in plastic wrap and aluminum foil before transport to the lab. After each drive, another rod is added to drill the next meter of sediments. Lake sediments are usually the consistency of toothpaste, green or brown in color, and have an earthy odor. Hitting an impenetrable surface usually indicates that bedrock has been reached, and the drilling is finished. About eight people or three packhorses are required to transport the gear to a lake. The actual coring process involves three or four people and in the summer, it takes place from a platform built across two inflatable rafts anchored in the middle of the lake. In winter, we use the ice surface as our coring platform, but deep snow and frigid temperatures often limit access.





▲ PHOTOS 3.1 & 3.2 Cores in the Yellowstone region are often collected in the winter when the crew can work on the frozen lake surface (above). (Melynda Harrison) A hole is be drilled through the ice and the coring device is lowered into the sediments to retrieve a series of sediment cores. Each core is extruded and wrapped in plastic for transport to the lab (below). The cores consist of soft consolidated sediment and the layers describe the environmental conditions at different times in the past. (Jack Fisher).

Although fieldwork may be the most fun, it is the research questions that motivate the project (and usually the funding) and the selection of sites and methods. A good research question is one that has importance beyond the boundaries of the study. Ideally, it is one that addresses a timely or broader scientific question or that proposes to look at old findings with a new, possibly transformative approach. In addition, such a research question must be answerable by a carefully crafted study and thoughtful selection of study sites. A good question ultimately leads to new questions and research directions.

Back in the laboratory is where the hard work takes place. The cores of sediment are unwrapped, sliced



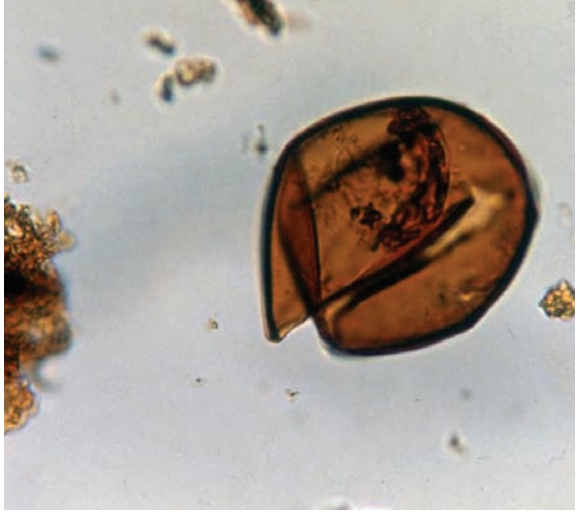
▲ PHOTO 3.3 The sediment cores contain pollen and charcoal that are analyzed in the laboratory to reconstruct the climate, vegetation, and fire history. This core was taken from a floating mat at the edge of Blacktail Pond in northern Yellowstone National Park. (Christy Hendrix)

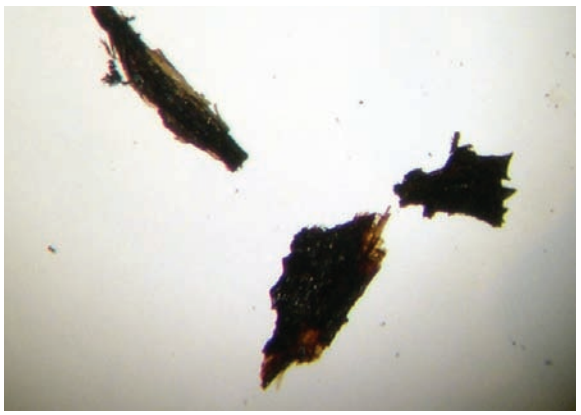
longitudinally, photographed and described. We then subject them to various types of analysis in order to learn three things about the past ecology – watershed history, age, and the prehistoric ecology of the lake. The lithology or physical composition of the core provides our first clue about the history of the watershed. For example, the base of most records consists of inorganic clay and silt. This indicates rapid deposition in a sparsely vegetated landscape and unstable slopes. Higher up the core, closer to the substrate surface, the sediments become organic, and this transition marks the time that the climate warmed, the lake became biologically more productive, and the watershed was stabilized by soils and plants. Samples are taken to determine the organic and carbonate ($CO_3$) content of the sediment and the mineral content, all of which can tell us about levels of biological activity in the past. Moreover, variations in the carbonate content of the sediments are often a good measure of chemistry and pH changes related to water temperature.

Paleoecologists are obsessed with time, even though our ability to measure it is often not very precise. Chronologies for our historical information are based on radiometric dating methods, including Carbon-14 ($^{14}C$) or Lead-210 ($^{210}Pb$) age determinations. Radiocarbon measurements are made on small wood or leaf fragments of terrestrial plants, on charcoal particles, and sometimes on the organic component of the lake sediments. Yellowstone lakes also contain volcanic ash layers, most notably the ash from the eruption of Mount Mazama, 7676 years ago that led to the formation of Crater Lake in southwestern Oregon. Refinements in radiometric age determinations are continually underway, and through time, the precision and accuracy have improved.

The assemblages of pollen grains in the core are the record of past vegetation. Pollen is produced by angiosperms (flowering plants) and gymnosperms (seed-producing plants). Not surprisingly, wind-pollinated species produce lots of pollen each year and more of it is deposited in the lake sediments than that of insect-pollinated species. Sediment samples are taken at regular intervals in the core, and these are treated with a variety of acids and bases to dissolve all the constituents except the pollen grains. The residue of pollen is mounted on glass slides and examined under the microscope at magnifications of 400-1000x. Different plants produce distinctive and often ornate pollen grains between 25-100 microns in diameter that are identified by comparing them with modern reference material and illustrations in published atlases.

Typically, 300-400 pollen grains are identified and tallied for a given sample in the core. It takes a trained analyst two or three hours to "count" all the pollen grains on a microscope slide. Our ability to identify a pollen grain to a particular plant species or genus is variable and limits our interpretation in some cases. For example, grass





▲ PHOTOS 3.4 & 3.5 Photomicrographs of Douglas-fir pollen (above). (Rudy Nickmann) and charcoal particles (below). (Tom Minckley)

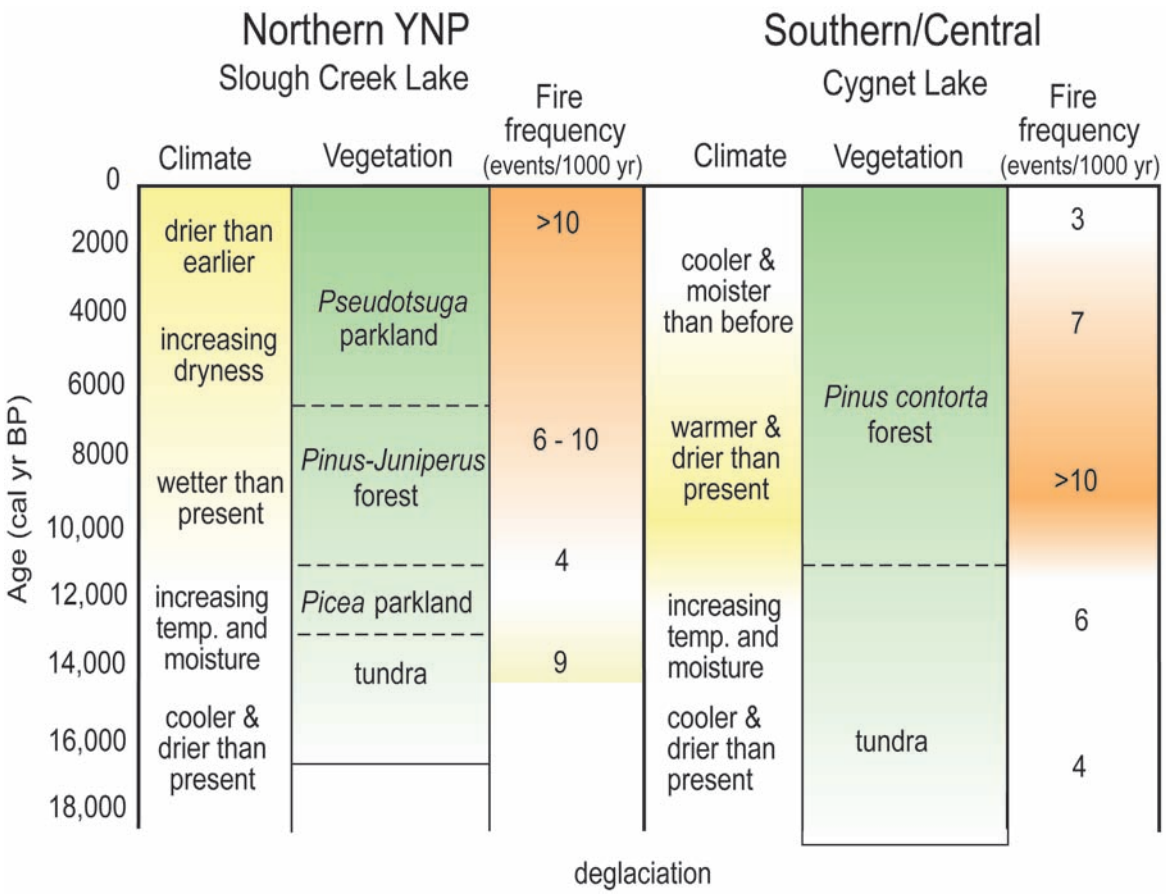
pollen cannot be identified below the taxonomic level of family (Poaceae), so it is not possible to determine whether the grass pollen comes from alpine or steppe species. Pine pollen in the Yellowstone region can be divided into two groupings: lodgepole/ponderosa (*Pinus contorta* or *P. ponderosa*) and whitebark/limber (*Pinus albicaulis* or *P. flexilis*) types. Other taxa, like meadow rue (*Thalictrum*), are secure identified to the level of genus. The presence of seeds, needles and other plant remains in the core often provide species identifications in cases where pollen cannot. In Yellowstone, pine dominates the pollen record because the conifers produce large amounts of pollen in the early summer, and the grains, which have two large air bladders, are easily carried by the wind. Sagebrush (*Artemisia*) also produces abundant pollen, and it blooms in late summer. A typical pollen record will include about 50 different trees, shrubs, and aquatic plants, but most of the pollen grains come from pine and sagebrush.

Pollen counts at each level are converted to percentages and accumulation rates. Changes in the proportion of different taxa through time are the basis for interpreting past vegetation. Because pollen does not have a 1:1 relationship with the plants that produce it, modern studies are needed to interpret past pollen assemblages. Modern pollen information comes from the surface sediments of lakes, and there are hundreds of samples from the U.S. to provide necessary calibration. Modern pollen samples, for example, indicate that pine pollen is overrepresented given the abundance of the tree in the watershed, but Douglas-fir (*Pseudotsuga mensiezii*) pollen is underrepresented.

Fire-history information is based on changes in the abundance of charcoal particles preserved in lakes, and our research in Yellowstone has help guide fire history investigations around the world. For ten years following the 1988 fires, we monitored the input of charcoal into lakes in burned and unburned watershed and were rewarded with a rich understanding of how charcoal data register fire patterns across a large natural region. Information from the 1988 fire has improved our interpretation of longer charcoal records in terms of past fire activity. For example, we can determine how often the area burned, the intensity of the burn, and the fuel type.

We begin by extracting charred pieces of wood and leaves from contiguous one-centimeter intervals of the core and examining them under the microscope. The data are converted to charcoal accumulation rates (number of particles/$cm^{-2}\,yr^{-1}$). Slowly varying changes in charcoal abundance describe long-term variations in fuel types. For example, forests produce more charcoal than tundra. Charcoal peaks represent individual fire episodes, and they can be summarized to calculate fire-episode frequency. Shifts in abundance between grass and wood charcoal disclose changes in fire regime from surface fires, which burn the ground vegetation, to crown fires that advance through the tree tops with serious consequences to the forest.

My interest focuses primarily on past vegetation and fires, but other fossils and chemical constituents in




▲ FIGURE 3.1 The climate, vegetation and fire history at Slough Creek Lake near the Lamar Valley and Cygnet Lake near Hayden Valley are based on pollen and charcoal analysis of radiocarbon-dated sediment cores. The pollen data suggest the development of open Douglas-fir parkland in the last 7000 years at Slough Creek Lake as the climate become drier and fire frequency increased. At Cygnet Lake, lodgepole pine forest has been present for the last 11,000 years. Fires were most frequent between 11,000 and 7000 years ago. Fire activity has decreased in the last 7000 years as the climate has become cooler. (Sarah Millspaugh)

lake sediments are examined by specialists to reveal different aspects of ancient environments. Diatoms, the skeletons of microscopic algae, reveal changes in the lake biota that can be tied to changes in nutrients, water temperature, pH, and light penetration. Carbon and oxygen isotopes trace the history of water inputs and evaporation through time that are related to climate. Insects and other animal remains document changes in insect outbreaks and zoological activity, and chemical changes reflect nutrient and erosion inputs related to variations in watershed characteristics. Multidisciplinary studies, like those underway at Crevice Lake in northern Yellowstone, are collaborative efforts to use many data sets to reconstruct the past.

### *What Have We Learned?*

From the first studies in the 1970s to ongoing investigations, we are gaining a better understanding of the Yellowstone ecosystem and its sensitivity to environmental change. New findings about Yellowstone's past range from information about the plants and animals that colonized deglaciated landscapes to insights on how Yellowstone's climate history fits into the larger picture of climate change in the western U.S. For me, both local and large-scale reconstructions are equally rewarding lines of inquiry. It is thrilling to stand on the shores of Crevice Lake and imagine the forest changes over several thousand years. It is also stimulating to join multidisciplinary teams, including paleoclimate modelers, to compare the evidence of past climate change across the continent. What follows are four topics where paleoecologic studies from Yellowstone have led to discoveries that were initially unexpected, but now seen to be scientifically quite important.

## GEOLOGY MATTERS

Today, the vegetation of Yellowstone is strongly controlled by geology and its influence on soil conditions. The broad volcanic plateaus of the region support nutrient-poor, well-drained soils, derived from rhyolitic rock. The lack of calcium and potassium and the dryness of the soils limit the success of most conifers on these surfaces. Lodgepole pine over most of its biogeographic range is considered a disturbance-adapted tree, but on rhyolitic substrates (and other well-drained soils), it is the dominant conifer from early to late stages of forest development, generally in the absence of other competitors. Yellowstone's lodgepole pine forests are considered subalpine in the strict sense, and on more nutrient-rich soil types, comparable elevations would support forests of Engelmann spruce *(Picea engelmannii*), subalpine fir (*Abies bifolia*), and possibly Douglas fir. Another way of thinking about this is: had the massive volcanic eruptions not occurred and laid down broad plateaus of rhyolite, the forests (and landscapes) of central Yellowstone would have resembled those of the nearby Teton and Gallatin ranges. The vast areas of lodgepole pine forest thus are an important legacy of the Yellowstone hot spot and provide a direct feedback to the fire history of the region.

Pollen records from the rhyolitic region shed some light on the importance of geology on the development of central Yellowstone's forests. Following an early period of tundra vegetation, which developed as the last glaciers were melting about 15,000 years ago, the region was invaded by lodgepole pine, and lodgepole pine forests have persisted ever since. This is despite climate changes that have transformed the vegetation in other parts of the Park and region. This attests to lodgepole pine's resilience (some call it a weed) to variations in climate when it occupies poor-quality substrates that limit competitors.

In contrast, pollen records from intermediate andesitic substrates in the south and east, and nutrient-rich calcareous glacial deposits in the north, reveal a more dynamic vegetation history. Following the early tundra period, those regions were colonized by a subalpine forest of spruce, fir, and whitebark pine. As the climate continued to warm, lodgepole pine and Douglas fir moved into the region. We believe that between 11,000 and 7,000 years ago, Yellowstone experienced warmer conditions than today, and this is evidenced by the abundance of Douglas fir pollen at sites that are presently too high for it to grow. As the climate cooled and became wetter during the last 7,000 years, the pollen data suggest that spruce, fir, and pine forests became more common again. If Yellowstone were not a hot spot with active rhyolitic volcanic eruptions, the history of the central region would surely be like the southern sites, and much of the Park would be covered by forests of spruce, fir, and pine. If the region had not been glaciated, the northern part of the Park, in particular, would not have been mantled by glacial till deposits rich in calcium and potassium, and the Northern Range (so-called because this is the northern winter range of Yellowstone elk) would have been a closed forest unsuitable for the winter range of ungulates it supports today. What makes Yellowstone so interesting is that all of these geologic events did occur and combined to shape the present-day ecosystem and ultimately the management challenges of tomorrow.

## FIRES HAPPEN

Studies of annual rings of living trees in the Park suggest that the last large fires, comparable to those of 1988, occurred between 1690 and 1730. This is a rather short time span for understanding the frequency of large infrequent fires, and we thought that perhaps the abundance of charcoal particles in lake sediments might allow us to extend the fire history beyond the tree-ring archive. Our modern charcoal studies, initiated with the 1988 fires, helped guide our examination of the ancient charcoal record and how it might be interpreted. In essence, the 1988 fires allowed us to "calibrate" charcoal records by providing some basic methodological information: How charcoal particles got into lake sediments? How far did they travel? What size of charcoal best described a local fire? What processes introduced charcoal into the lake, and how long did it take for burial in the sediments?

A fire-history study of Cygnet Lake, located on the rhyolitic Central Plateau, was undertaken by Sarah



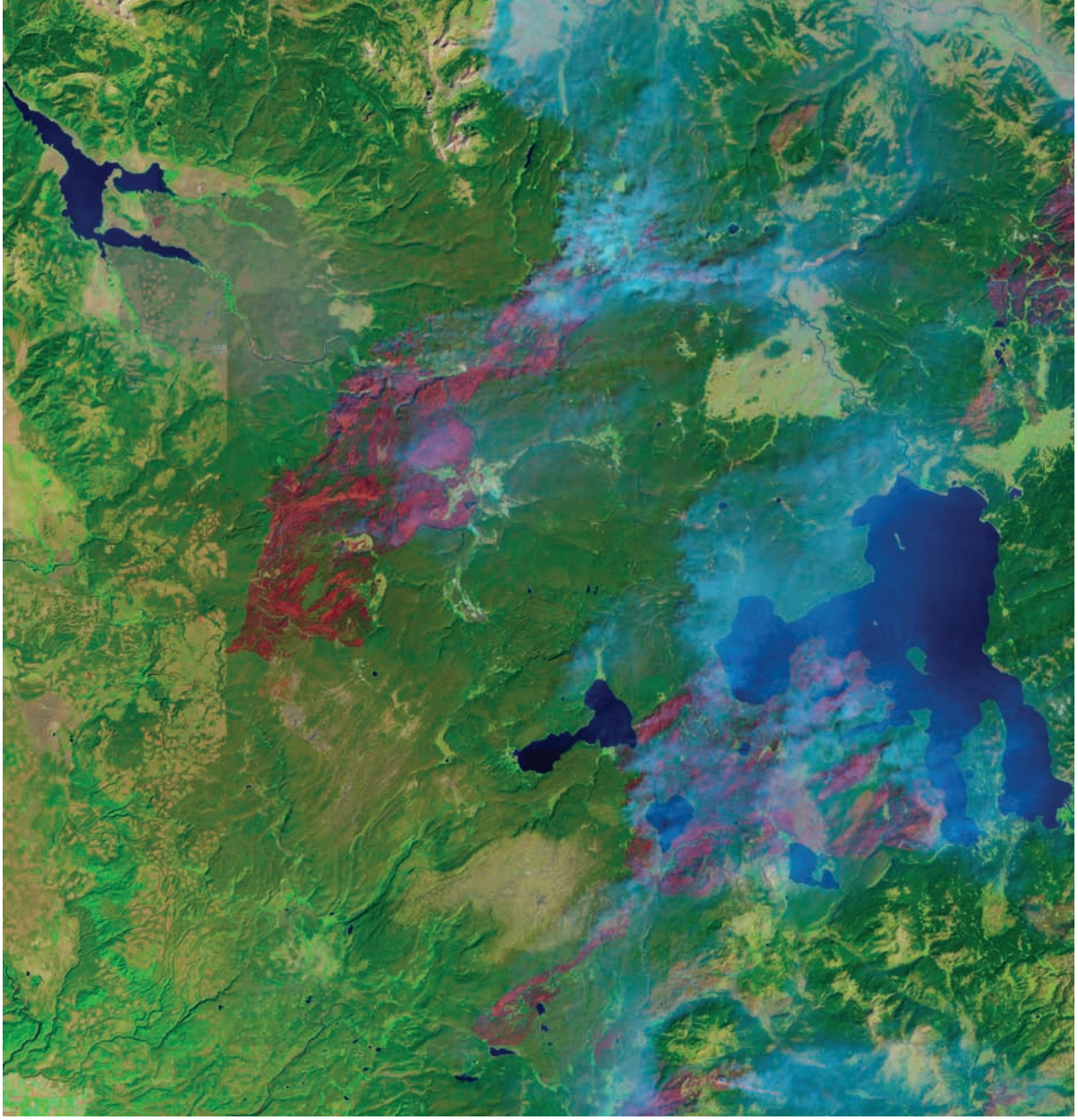
▲ PHOTO 3.6 This photo was taken during a fire in 1939 in the Lewis Lake area. Evidence of this and previous fires is found in the layers of charcoal deposited in lake sediments. (NPS, Yellowstone National Park)

Millspaugh as part of her dissertation. Her research showed that many peaks of charcoal (i.e., fire episodes) occurred in sediments dating between 11,000 and 7000 years ago. In the last 7000 years, the charcoal data suggest that fire frequency steadily decreased leading to the present interval of 300-400 years between large events. The increase and then decease in fires is remarkable, considering that the pollen data indicate that the lodgepole pine forest surrounding the site did not change. This juxtaposition of changing fire occurrence in the absence of changing fuels shows how closely fire activity is tied to climate; fire regimes can change even when forest composition does not. Cygnet Lake and other charcoal-based fire studies in the western U.S. make us realize that large fires do not occur at regular predictable intervals. Instead, the charcoal records indicate that fire frequency has tracked climate change over millennia, and as climate has changed so too has the frequency of fire events. This understanding of long-term fire dynamics is perhaps one of the most important discoveries that came out of the 1988 fire research.

## CLIMATE MATTERS

It is not possible to appreciate Yellowstone's ecological history without recognizing the importance of climate changes that have affected the entire western U.S. From independent data and paleoclimate modeling, we know that the presence of continental ice sheets and variations in solar radiation through time have affected latitudinal temperature gradients, shifts in the location of storm tracks, and the strength of large-scale atmospheric circulation patterns and precipitation regimes. One prominent control of climate since the last ice age has been the variations in the seasonal cycle of insolation (incoming solar radiation) caused by variations in the tilt of the Earth's axis and the season of perihelion (when the Earth is closest to the Sun). Between 11,000 and 7000 years ago (the early Holocene), perihelion occurred in summer rather than in winter as it does today, and the tilt of the Earth was greater than present. As a result, insolation was 8.5% greater in summer and 10% less in winter at 11,000 years ago at the latitude of Yellowstone. By 6000 years ago, summer insolation was still higher than present, but less than before, and by 3000 years ago, levels were close to modern. The early-Holocene amplification of the seasonal insolation cycle caused an expansion of the northeastern Pacific subtropical high pressure system, which intensified summer drought in the Pacific Northwest. Conversely, strengthened summer monsoonal circulation in the American Southwest at that time increased summer rainfall in that region. These large-scale climate changes are evident in the vegetation and fire history of Yellowstone.

The early Holocene is the most extreme warm period of the last 15,000 years, and the climate impact on the Yellowstone region has received a lot of research attention. Today, Yellowstone lies at the transition between areas under the influence of the subtropical high and those strongly affected by summer monsoons. As a result, there are two precipitation regimes in the Park at



▲ FIGURE 3.2 This landsat satellite image shows that large fires, like those of 1988, are characterized by a mosaic of different burn severities. The 1988 fires left some forest stands untouched while others were destroyed. Postfire vegetation recovery in the past can be studied from pollen analysis. (USGS, Earth Resources Observation and Science Center)

present. The southern and central region and the highest elevations have a Pacific Northwest climate (so-called summer-dry region), wherein the influence of subtropical high leads to relatively dry summers. The northern part of the Park receives more of its annual precipitation in summer as a result of its comparatively drier winters and greater summer monsoonal activity (summer-wet region), and summer thunderstorms are also more likely in this region.

Paleoecological data and paleoclimate modeling indicate that the two precipitation regimes were strengthened in the early Holocene by the higher-than-present summer insolation. The southern and central parts were drier than today, because the subtropical high pressure system was stronger then than it is now. Northern Yellowstone was effectively wetter in summer as a result of the intensified monsoons. Charcoal records from sites in the northern part of Yellowstone show low fire activity then, progressively more fires in the last 7,000 years as

the region dried. Sites in the central and southern Park, including Cygnet Lake, indicate highest fire activity in the early Holocene when the aridity was greatest, and fewer fires since then as cooler wetter conditions established. Sites in the northern range, like Slough Creek Lake, show the opposite pattern of fewer fires before 7000 years ago and more fires since then.

The ideas developed in Yellowstone have become an organizing framework for paleoclimatic research in the western U.S. Follow-up studies, testing the summer-wet/summer-dry climate hypotheses, have been conducted in the Wind River Range, the Bitterroot-Selway, the southern Rockies, and the Beaverhead Range. Together, these studies provide a much clearer picture of how the climate system works and the influence of mountains in creating regional differences.

Why is the study of climate conditions 15,000 years ago important? It suggests that adjacent regions can have quite different climate responses as a result of the local influence of continental-scale climate changes. The spatial patterns result from the interplay between atmospheric circulation and mountainous landscapes. Similar complex interactions will surely be an important factor with future climate change. Evidence for the persistence of two precipitation regimes offers testable research hypotheses about the availability of resources for wildlife and prehistoric peoples at different times in the past. Such hypotheses can help direct interdisciplinary research at a broader scale. Consider the Yellowstone Lake region in the early Holocene as an example. Humans were living in and around Yellowstone during the early Holocene but the archeological evidence is too sparse to reconstruct their activities. We expect that their resource base was strongly dictated by the climate and environment. Given our understanding of the paleocological record, early-Holocene winters were colder than today as a result of low winter insolation, and perhaps as important, mid-winter thaws were infrequent. Such conditions would have discouraged overwintering of game in the Park, and winter food sources for year-round occupation would have been scarce. A rapid rise in spring and summer insolation in the early Holocene would have led to an early thaw, rapid snowmelt, and early ice breakup on Yellowstone Lake. Spawning of Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*) in the tributary streams is tied to the timing of peak stream flow and this would have occurred earlier in the year in the early Holocene.

In contrast to the severe winters, summer and fall conditions had many attributes that would have encouraged human occupation. Frequent fires in the summer-dry regions of Yellowstone would have kept much of the forest in early successional stages, although average fire size may have been relatively small. Based on forest development following modern fires, the diversity of birds and mammals in young forests would have generally been high, which may have improved hunting success in the summer. Yellowstone Lake temperatures would have been higher-than-present in summer and fall, and fish may have been an important early summer food source (although there is no archeological evidence of this to date). Dry warm weather in fall would have extended seasonal occupation. Greater radiative fog from a warm lake, however, may have shifted the location of campsites away from the shore to rocky promontories during the fall. So, one can hypothesize that a warmer climate, a warmer lake, and more open forests would have enhanced food resources between 11,000 and 7000 years ago compared to present.

**HUMANS MATTER (BUT HOW?)**

We've been involved in two investigations to ascertain whether changes in land management were significant enough to be registered in the recent environmental records of Yellowstone. The first study was done eighteen years ago, when colleagues from the University of Minnesota and I undertook a study of the last 200 years of Yellowstone's history. We were interested if there was evidence of environmental change in the sediments of small lakes in the northern range following the creation of national park in 1872. In particular, we were looking for possible effects caused by changes in winter ungulate populations, such as increased erosion or nutrient enrichment in lakes during times of high elk and bison numbers. If such evidence was found, they might be attributable to changes in Park management,



▲ PHOTO 3.7 Climate change in the region threatens the health of whitebark pine - an important source of food for many animal species including red squirrels, Clark's nutcrackers, and grizzly bears. Across its range, nonnative blister rust and native mountain pine beetle have attacked whitebark pine. Increased temperatures projected for the future are likely to increase whitebark pine mortality in the Yellowstone region. (Big Sky Institute, MSU)

particularly to natural regulation, which began in earnest in the 1970s. The research involved sampling the uppermost sediments of five small lakes in the Northern Range, dating the sediments with $^{210}$Pb dating methods (which is good for the last 200 years), and analyzing the fossils and chemistry of the sediments for signs of environmental change. The largest signal that we obtained came from Floating Island Lake near Tower Junction. There, detection of erosion came only at the time of road construction. At other sites, the diatom assemblages indicated times of nutrient enrichment that might have been caused by heavy ungulate use at the lakes, but the timing of enrichment was not synchronous from one watershed to the next. In the case of aspen, some records showed a decrease in aspen pollen in the 20$^{th}$ century, but others indicated no change or even a slight increase. None of the records detected a decline in aspen in the last 150 years, and we surmised that aspen is poorly represented in recent centuries in comparison to its prominence at the end of the glacial period. Some lakes revealed changes in sedimentation rate, but again, no widespread change was detected that might correspond with historic fluctuations in elk number.

This study has been more recently expanded upon by the investigation at Crevice Lake in the Yellowstone River canyon. Pollen, geochemistry, paleomagnetism, and diatoms records, examined at decadal resolution over the last 2600 years, suggest that the last 200 years of environmental history has been relatively complacent, compared to dramatic adjustments in the lake and watershed that occurred in response to climate changes between BC 150 and AD 1100. We can find comfort from the combined findings of two investigations, which imply that Yellowstone today is a relatively pristine, naturally functioning ecosystem. Human-related impacts of the last two centuries have left little trace in the sediments of lakes, and by all measures, most pale in comparison to natural variations of the more distant past.

Yellowstone now faces threats from an ever greater human footprint in the region and globally, and projected changes in the region seem likely to exceed the natural range of variability. Future climate model projections scaled down to the Yellowstone region suggest changes in temperature and precipitation that will affect the distribution of Yellowstone's species, assuming that they can keep pace. Present climate projections focus on the consequences of doubling $CO_2$ in the atmosphere - something that is now projected to occur sometime this century. Under a 2x$CO_2$ scenario, model projections suggest that the Yellowstone region gets warmer in both summer and winter, summers get drier (as a result of warmer temperatures), and winters become wetter as levels of greenhouse gases increase. Warmer, wetter winters imply more rain, less snow, earlier snowmelt, and longer summer conditions. Measurements taken in the last 20 years suggest that this climate trend is already underway.

The biogeographic range shifts associated with future climate change are dramatic and will not be easily attained given the fragmented landscape of the region. Species' responses will also be complicated by sharp elevational and latitudinal gradients and trade-offs in precipitation discussed previously. High-elevation organisms will likely be the most impacted because climate warming will shift suitable habitat to ever higher elevations, and eventually, no elevation in the Yellowstone region will be high enough to sustain viable populations. Whitebark pine is an example of a highly vulnerable species in this regard, and its viability is further compromised by outbreaks of mountain pine beetle (*Dendroctonus ponderosae*). The seeds of this conifer are an important food resource for grizzly bear (*Ursus arctos*), red squirrel (*Tamiasciurus hudsonicus*), and its loss could lead to the collapse of a vital ecosystem in the Park.

Future changes in the biogeographic range of tree species raise equally great concerns for Park resource managers. For example, some species are projected to find suitable conditions in the Yellowstone region in the future that don't grow there today. For example, warmer conditions may allow Gambel's oak (*Quercus gambeli*) to extend its range northward from Utah and Idaho into northwestern Wyoming. At the same time, projected warmer wetter winters resemble those found today in the interior Pacific Northwest, and habitats suitable for wet-loving conifers, like western larch (*Larix occidentalis*) could also exist in Yellowstone in the future. Thus, the studies to date suggest that some species will survive with little change (e.g., lodgepole pine), the ranges of others will shift from the south or north, and some species (e.g., whitebark pine) will be lost from the region altogether.

Such equilibrium-based climate and species projections are unsatisfying on several levels, and there is an urgent need to improve them. For example, it is not clear if species are capable of naturally adjusting their range at the rate required to keep pace with projected climate change. Studies elsewhere suggest that species will have to move 40 times faster than anything we've seen in the fossil record. Movement today and in the future will also have to occur across diverse landscapes with many barriers and different land uses. What will be the impact of fragmentation? And, if the rates are too rapid, what opportunities does this create for non-native species and weeds to invade weakened native communities? Human intervention and directed assistance are used on commodity lands to move economically important species to new areas, but is this appropriate for national parks and wilderness areas as well? Certainly, the answers to these questions depend to some degree on particular land ownership and management goals, but they also point to the need for discussion among different stakeholders, coordinated responses, and stepped-up monitoring and inventory efforts. We are at the stage in resource management where climate change science will become a part of every natural resource policy discussion in the Greater Yellowstone Ecosystem and other natural ecosystems.

## *Conclusion*

Paleoecology is a fascinating subject in its own right, but, more than that, the scientific discoveries that it provides are the foundation for understanding current and future ecosystem dynamics. Without information about the natural range of environmental variability, it would be impossible to evaluate changes evident today or likely to occur in the future. It would also be difficult to assess human impacts, including the consequences of management decisions at the local scale or anthropogenic climate change at the global scale. In the Yellowstone region, knowledge of the past has led to renewed appreciation of the importance of geology, climate and climate change, and natural disturbance in shaping the diversity of plant and animal communities that exist today. It has also pointed to new research areas to examine how prehistoric peoples and early Euro-Americans may have utilized natural resources in the past. Finally, paleoecologic information provides insights into the range and rate of environmental changes that will help us evaluate current human-induced change.

Not all is known about Yellowstone's past, and in most respects, our understanding is rudimentary and incomplete. For example, recent drought in the region is profoundly altering the landscape and drying

up wetlands for the first time in Park history. What is not clear is whether drying of this magnitude has ever occurred before and what the lasting ecological consequences might be. Such information would help resource managers to assess the current peril. We also have limited knowledge about the processes that link different components of the ecosystem. What, for example, are the natural drivers of limnologic change? Is it changes in terrestrial inputs, changes in climate, or biotic interactions within the lake itself? And, what are the linkages between climate change, fire activity, and the infestation of forest-insect pathogens, such as occurring at present.

Our ability to address nuanced questions about ecosystem processes is aided by new techniques, better conceptual and numerical models, and well-dated high-resolution data sets. The paleoecologic research that began in the Yellowstone region in the 1970s still holds the key to critically important questions, and those mysteries will motivate creative scientific investigations for decades to come.



▲ PHOTO 3.8 Winter recreation, such as skiing and snowmobiling in the Greater Yellowstone Ecosystem, are likely to be affected by climate change as the region experiences reduced snowpack and fewer cold days. Some businesses may be able to diversify the types of recreational activities they offer based upon the changing climate. Communities where recreation is an important component in the local economy and lifestyle may face significant challenges in the near future. (Jerry Johnson)