Response of Sierra Nevada Vegetation and Fire Regimes to Past Climate Changes[1]

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The study of changing vegetation patterns within forested communities of the Sierra Nevada has had a long history, initiated by the great naturalist John Muir. More recently, paleoecologists, who study ecosystems of the past, have analyzed fossil plant remains recovered from lake and meadow sediments to understand the regional biogeography and disturbance history of Sierra Nevadan forests. This research on paleo-historical vegetation associations has increasingly attracted the attention of land managers and others for several reasons, including the potential that future climate changes will cause rapid and substantial changes in vegetation composition, fire occurrence, and insect infestation.

Plant communities are continuously stressed by environmental change, such as natural disturbance, climatic perturbations, and human activities, and exhibit variation in structure and species composition on several time scales. Some agents of change such as humans, fire, and insects operate over time cycles of years to decades. Records of their effects are often gleaned from historical accounts, matching photographs and individual trees. At the other end of the time scale are extremely long-term changes—those caused by movements of the Earth's crust, such as the rise of the Sierra Nevada itself, occurring on the order of millions of years. But changes in vegetation linked to climatic perturbations occur on the order of hundreds to thousands of years. Evidence accumulating over the past several decades makes it clear that on this intermediate timescale, climatic change is the primary driver for major vegetation changes. Although it is easier to refer to forests as assemblages of plant species, each species actually responds individualistically to varying climatic parameters. When viewed over intermediate timescales, then, vegetation associations appear to be merely temporary aggregations of species.

Former forested ecosystems can be reconstructed by using a combination of paleoecological "tools." The most useful are pollen and plant macrofossil remains from the species that formerly grew in a particular area. Analysis of these plant remains allows identification of the important forest species at different times in the past. Analysis of charcoal particles allows reconstruction of former forest fire regimes. Plant remains and charcoal particles are concentrated from lakes, meadows, and wetlands by extracting sediment cores from those deposits. Several types of sediment corers have been used in the Sierra Nevada, including stationary piston corers, such as the Livingstone corer.

The Sierra Nevada is, arguably, the most studied mountain range of its size in the Western Hemisphere. Presently, information on former vegetation has been gathered at more than 70 sites (Anderson and Smith 1997). More sites are on the western side of the crest than on the east, owing to its gentler topography and larger number of sedimentary basins.

The balance of this paper concentrates on three time periods of substantial past vegetation change for the Sierra Nevada. The history of forest disturbance, primarily fire, during these

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time periods is also briefly described. The time periods include (1) the late glacial, with anomalous plant assemblages compared to today; (2) the early Holocene, which was dominated by pines; and (3) the middle to late Holocene which saw the development of the modern forests of today.

The late glacial time period, defined here as occurring from approximately 18,000 to 11,000 radiocarbon years ago was a time of active redistribution of plant species in nearly all regions of the world. The great ice sheets of the Northern Hemisphere reached their maximum extent and had begun to melt. Their influence on climatic patterns, along with ongoing changes in Earth's orbital parameters, caused climatic conditions that were very different than those of today. One presumably representative location in the Sierra Nevada that has provided a rich record of past vegetation for this time period is Swamp Lake in Yosemite National Park (Smith and Anderson 1992). Although today the site is surrounded by species characteristic of the lower montane forests (conifers and hardwoods), during the late glacial period, the forest around the lake contained a wider variety of trees characteristic of today's montane, upper montane, and subalpine forests. Of particular interest is the former occurrence around the lake of mountain hemlock (*Tsuga mertensiana*) and incense-cedar (*Calocedrus decurrens*), which rarely occur together today and occupy very different climate space at present (Thompson and others 2000).

In general, the elevational ranges of most forest species in the late glacial period were depressed by about 1000 meters in the Sierra Nevada relative to today (Cole 1983). On the west side of the crest, subalpine conifers probably grew with sagebrush in forest openings at approximately 2000-m elevation, while xerophytic and mesic conifers grew at approximately 1000-m elevation. Giant sequoia may have grown along watercourses at lower elevations. Modern Great Basin species grew in the San Joaquin Valley, suggesting that the biogeographic boundary between the Sierra Nevada and the Great Basin (today found at the Sierra Nevadan crest) occurred at least 100 km further west (Davis 1999).

By the Early Holocene, defined as approximately 9,000 to 7,000 radiocarbon years ago, much of the Sierra Nevadan ice cap had melted, and most common tree species in the Sierra Nevada had migrated to higher elevations than their ranges during the glacial period. Higher-elevation forests during this time period were primarily dominated by different pine species, with montane chaparral shrubs in forest openings.

A particularly good record exists for lodgepole pine (*Pinus contorta* var. *murrayana*) (Anderson 1996). The species was widely established within its modern elevational range between 9,000 and 10,500 years ago. During the early Holocene, lodgepole pine remained a key component of montane forest assemblages below its present range. The species disappeared from most lower-elevation sites between 6,750 and 9,000 years ago. The Sierra Nevada forests were more open than today, as suggested by a greater occurrence of sagebrush (*Artemisia*) and many montane chaparral shrubs, such as bush chinquapin (*Chrysolepis sempervirens*) (Anderson and Smith 1994). Giant sequoia moved upslope and may have even grown above its present elevational range (Davis and Moratto 1988). The lower montane forest may have been partly dominated by oaks (*Quercus*) (Anderson and Smith 1994).

The record of vegetation for the middle to late Holocene, from approximately 6,000 radiocarbon years to the present reveals differentiation and development of the vegetation associations we see today. Four conifer species have provided us with an excellent record, demonstrating vegetation and climate change during this time. Pollen of white and red fir (*Abies concolor* and *A. magnifica*) and mountain hemlock suggests that during the early Holocene these species were only minor components of the Sierra Nevada forests. However, by approximately 6,000 years ago, each of these species increased in abundance, perhaps largely in response to changing climate and higher soil moisture levels (Anderson and Smith 1994). Similarly, after approximately 4,500 radiocarbon years ago, the range of giant sequoia (*Sequoiadendron giganteum*) expanded (Anderson 1994). The abundance of

montane chaparral shrubs declined in Sierra Nevada conifer forests as the forest canopy closed (Anderson 1990).

What would account for the gradual but important changes that occurred in Sierra Nevadan forests during this period? Because each of the tree species that increased during the late Holocene depends upon readily available soil moisture during the summer growing season, it has been suggested elsewhere (Anderson 1990) that either a reduction in the length of the summer dry season, an increase in precipitation during the winter months (as snow, lasting longer into the spring), a reduction in temperature causing reduced evaporation, or some combination of these processes would have favored the above-mentioned conifers.

Several studies have provided evidence that explains the changes in biota seen in the fossil record for the past 18,000 years. First, the occurrence of massive North American ice sheets influenced the broadscale climate patterns in several ways. The Laurentide Ice Sheet, occurring up to 3 km thick in some places, diverted the Jet Stream to a more southerly position, bringing colder and mostly wetter conditions to the Sierra Nevada and the Southwest compared to today (COHMAP Members 1988, Thompson and others 1993). As the ice sheets melted, their influence diminished, and the average position of the Jet Stream migrated northward to its present position. Second, the Earth's orbital parameters have varied singly and in conjunction over time, changing the seasonal distribution of solar radiation for the Northern Hemisphere and affecting temperatures. Compared to today, summer insulation was 8 percent greater and winter insulation 8 percent lower during the transition from the glacial to early Holocene periods (Kutzbach and Guetter 1986). The net result was warmer summers and cooler winters than today, a situation that allowed a variety of conifers to grow in proximity to each other during that time. Later in the early Holocene, high levels of summer insulation led to warmer conditions during summer, causing progressive drying of soils and perhaps an intensification of Mediterranean conditions. During the middle and late Holocene, however, the difference between summer and winter insulation lessened, leading to a cooling during the growing season, a potential increase in winter precipitation and a reduction in evaporation. Groundwater tables rose (Anderson and Smith 1994), and these conditions favored species that require high levels of soil moisture.

What is the relationship between vegetation and climate change and the long-term history of forest fire in the Sierra Nevada? Recent work by Brunelle and Anderson (2003) at a site in the upper montane zone of Yosemite National Park shows highly variable occurrences of large-magnitude fires through time. The greatest fire activity occurred in the early Holocene, when climate was drier than today. However, another period of high fire activity occurred during the Medieval Warm Period approximately 850 to 575 calendar years ago in the Sierra Nevada (Graumlich 1993). Similarly, studies by Anderson and Smith (1997) for the mixed conifer forest showed very widespread fires in the Sierra Nevada about 700 calendar years ago, which probably corresponds to widespread fire at the end of the 13th century as deduced by tree-ring fire scar analysis (Swetnam 1993).

If, as we assume, fire occurrence depends on effective moisture and can be used as a proxy for climate, then the severe droughts that occurred during the Medieval Warm Interval are small when compared with those during the warmer early Holocene. If the atmospheric warming trends documented for the 20th century continue into the 21st century as projected, the record of vegetation and fire from these earlier time periods becomes an important record that informs us about the future of fire and vegetation change in the Sierra Nevada.

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