PAST CLIMATES, FORESTS, AND DISTURBANCES OF THE SIERRA NEVADA, CALIFORNIA: UNDERSTANDING THE PAST TO MANAGE FOR THE FUTURE

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ABSTRACT: The forests of the Sierra Nevada have been altered for millennia by climate, natural disturbances, and more recently by the activities of humans. Management of these forests and their resources as ecosystems to meet diverse objectives, requires an understanding of the conditions under which existing forests developed and how they have changed through time. Recently accumulated information suggests that the interactions of factors such as geographic position, topography, and shifts in climate have resulted in substantial spatial and temporal variation in the vegetation composition and structure of the forests of the Sierra Nevada. These forests are substantially different today than they were a century ago. The climate of the last 1,000 years appears to have been drier and wildfires were more frequent than at present. Consequently, the forests, especially pine and mixed conifer, were generally more open with fewer trees, but a greater proportion of larger diameter trees and fewer shade-tolerant or fire-intolerant trees. Although the evidence supporting this description of the average forest condition is persuasive, there is currently little information on the variation in forest structure and composition across the landscape and through time. Nor is there much information on the relations of other plants and animals to the changing forests. As forest managers seek to manage forests as ecosystems, information on the structural and compositional variation of forests in the Sierra Nevada through space and time should be used as the basis of management objectives.

Key words: climate change, disturbances, ecosystems, forests, Holocene, management, Pleistocene, Sierra Nevada

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Two objectives of ecosystem management are to (1) perpetuate ecosystems and their processes, and (2) provide for sustainable production of outputs such as timber, forage, wildlife for viewing and consumption, water for various uses, and recreational opportunities. Managing for these disparate objectives simultaneously, requires an understanding of the environmental conditions under which existing forests evolved. In the past, forests were neither stable in the long term, nor unaffected by humans. Forests were and are dynamic and ever-changing. They responded through time to the interactions of their topographic and geographic positions with a variable climate and various disturbances (both natural and anthropogenic) (Whitlock 1992, Blackburn and Anderson 1993).

To clearly understand the developmental processes that formed and influence current ecosystems, reconstruction of past environmental and ecological variation must be expanded beyond a few years or decades (Webb and Bartlein 1992, Scuderi 1993). Many of the dominant plant species in the forests of the Sierra Nevada are quite long lived or have seeds or spores that remain viable for long periods of time. These attributes allow them to survive periods when environmental conditions are unfavorable and take advantage of relatively infrequent periods favorable for regeneration or rapid growth. Thus, there can be significant lags in the change in vegetation composition and structure as ecosystems respond to the changing environment, and ecosystems probably rarely or never attain a state of equilibrium with their environment (Davis 1986, Sprugal 1991).

To successfully manage ecosystems, these longer-term environmental and ecological processes, and the resulting landscape patterns will need to be understood. Management of current ecosystems and patterns of biodiversity without a long-term perspective can lead to actions that may be detrimental to the long-term sustainability of those systems (Reice 1994). As an example, one objective of forest management in recent years has been to remove wildfire or substantially reduce its effects. These actions have contributed to a forest composition and structure that may not be sustainable and increases the probability of stand-replacing fires (Show and Kotok 1924, Biswell 1989, Agee 1994, Smith et al. 1994).

The Sierra Nevada and adjacent areas, such as Mono Lake, offer a good opportunity to study changes in ecosystems through time and to suggest models of forest structure which might be achieved through ecosystem management activities. The end of the last glacial period, some 12,000-15,000 years before present (YBP), provides a relevant starting point to examine ecosystem changes in the Sierra Nevada. The wealth of information available from tree-ring and fire-scar analyses, sediment cores, lake level records, historic photographs and journals, and other sources provide for development of approximate historic and future ecosystem characteristics (Foster et al. 1990). Thus, the subject area of this paper is the forested landscape of the Sierra Nevada, principally pine and mixed conifer forests, beginning about 12,000-15,000 YBP. Our objectives are to: (1) examine reasons for an ecosystem approach to forest management in the Sierra Nevada, (2) illustrate the variation in climate and ecosystem components of the Sierra Nevada through time, and (3) suggest an approach and target vegetation models for managing a variable, continually-changing forested landscape in the Sierra Nevada.

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FOREST HEALTH IN THE SIERRA NEVADA

Concern about the health of forests has recently become an important issue. Healthy forests are those capable of meeting desired resource objectives and are sustainable through time (Smith et al. 1994). Alteration of fire regimes, through fire suppression and the reduction of Native American caused ignitions, coupled with a shift in climate and changes in human disturbance patterns in the last 100 years, has resulted in increased tree densities, changes in stand structure and spatial patterns, and build up of dead, flammable material in many of the forests of western North America. Insects and other disease organisms have responded to these changes. Although, outbreaks of insects occurred prior to European settlement, they were relatively brief and spatially confined (Lieberg 1899, Swetnam and Lynch 1989, Wickman et al. 1993). These same insects now are affecting entire landscapes nearly continuously (Hessburg et al. 1994). The combination of change in forest structure and patterns of mortality results in fires that often burn with greater intensity than in the past (Biswell 1989, Agee 1994).

In the Sierra Nevada, many forests are in poor and, perhaps, declining health (Smith et al. 1994). Evidence supporting this conclusion include large acreages of densely stocked stands (too many trees present for available resources such as water and nutrients), outbreaks of insects and other mortality agents that have caused extensive amounts of tree mortality especially in white fir (*Abies concolor*) and ponderosa pine (*Pinus ponderosa*) over short time periods, and increases in the spatial extent of severe, stand-replacement wildfires.

PAST CLIMATES, FORESTS, AND DISTURBANCES OF THE SIERRA NEVADA

Methods and Data Limitations

The characteristics of past ecosystems of the Sierra Nevada are based on data sets developed from biotic materials and fossilized remains of organisms, as well as historic photographs and writings. Late Pleistocene and early to middle Holocene climates, soils and vegetation composition and structure are based on sediment cores. Late Holocene climates, shifts in the elevation of treeline, vegetation characteristics, and fire frequencies are based on tree-rings and fire-scars. Composition and structure since European contact are documented through photographs, historical writings, and landscapes not greatly disturbed by modern management activities but are undergoing frequent natural disturbance events.

Dates are from radiocarbon dating of biological material in sediment cores, and cross-referencing tree rings found in remnants of logs and stumps. Good tree ring chronologies can be developed with great accuracy through cross-referencing. Climatic characteristics, especially precipitation, are inferred from tree rings widths which measure how the precipitation and other factors influence tree growth (effective precipitation) rather than the absolute precipitation.

Study sites are often very local and replications tend to be few. Thus, topographic and microclimatic variation such as wind patterns, elevation, aspect, slope, and soils can influence interpretations of past landscapes. Meadows and lakes are the preferred sites for coring sediments for soil, charcoal, and pollen analyses, because they often yield well stratified long-term core samples. Cores from meadows and lakes, however, can be used as indicators of the characteristics of upland forests, but must be interpreted with caution.

Soil composition is inferred from the proportions of the different components in sediment cores. Soils are developed through weathering parent material and the deposition of material on the soil surface. Soil development and characteristics vary with climate, especially temperature and moisture, vegetation characteristics, kind and structure of parent material, and topography. Warm and moist climates; presence of forest vegetation; unconsolidated, permeable parent material with little lime; and flat or depressed topography all increase the speed of soil development. Erosion and subsequent deposition of soils in low spots, such as meadows and along water courses, can increase the depth and organic richness of the soils. Forest vegetation is associated with faster soil development than open, grass dominated areas (Millar et al. 1958). Interpretations of the rates of soil development, therefore, are highly dependent on the topography and hydrology of sampling sites.

Characteristics of vegetation and past patterns of wildfires are inferred from sediment cores. Larger fragments of charcoal, macrofossils, and Douglas-fir (*Pseudotsuga menziesii*) pollen are relatively heavy; their presence may indicate fire and vegetation characteristics close to the sampling point. In contrast, fine charcoal and pollen from plants such as oaks, pines, and composites are quite light in weight and can be carried by the wind for great distances. High concentrations of these material may indicate fire and vegetation characteristics of larger areas.

Historical photographs (Gruell 1994) and writings (Farquhar 1966) provide valuable information on the characteristics of the Sierra Nevada since European contact, but must be interpreted with caution. Historical material characterizing vegetation should not be assumed to represent common or mean conditions. Photographs and written notes, such as journals, often recorded or described a particular scene because it was of interest to the individual making the record within the context of the photographer's or writer's experience and the context of the landscape.

Forests that have not been appreciably affected by forest management and appear to be undergoing disturbances at rates expected under the current climatic influence are another source of information about past forest compositions and structures. Although unaltered areas are scarce, especially in ponderosa pine, mixed conifer, and eastside pine forests of the Sierra Nevada, there are examples in or relatively close proximity including the pine forests in the San Pedro Martir in Baja California, Beaver Creek Pinery, Lassen National Forest, isolated pine forests of Nevada , and remote areas of the Klamath Mountains.

The Sierra Nevada: Late Pleistocene to Recent Holocene (12,000-15,000 YBP to Present)

Climate. — Since the retreat of glacial ice from the Sierra Nevada, approximately 12,000-15,000 YBP, the climate of California has varied considerably. The last 3,000 to 4,000 yrs was cooler, with more effective precipitation relative to the rest of the Holocene (Fig. 1). Temperatures varied from cool to warm, and effective precipitation from wet to dry. However, temperature and precipitation did not always vary together (Moratto et al. 1978, Davis et al. 1985).

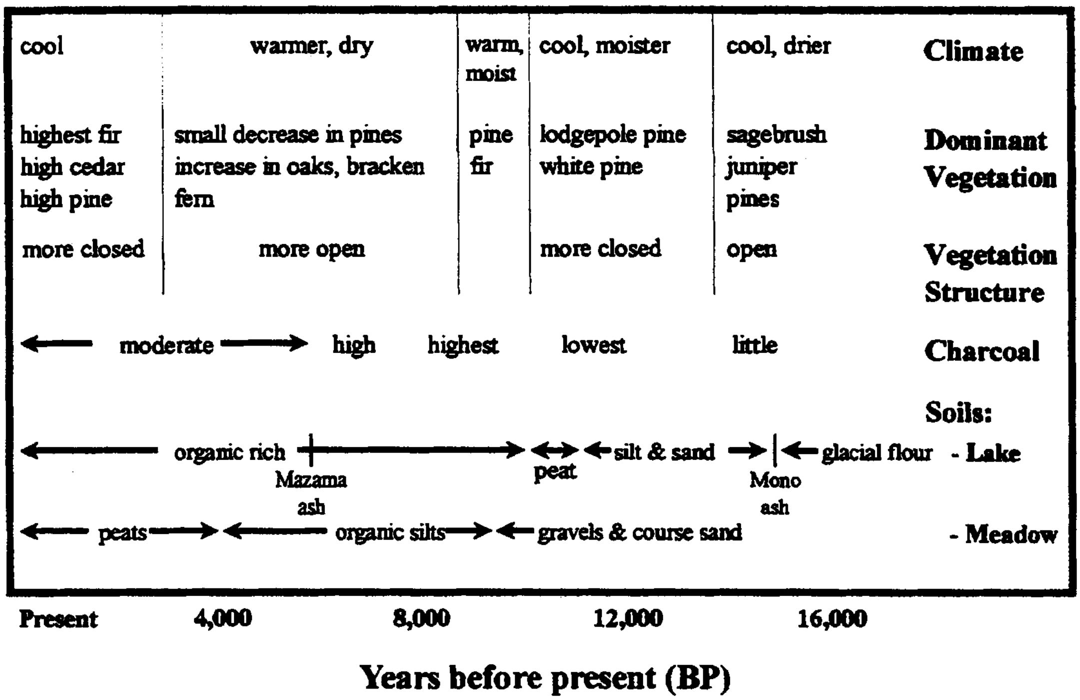

Fig. 1. Climate, dominant vegetation, vegetation structure, amounts of charcoal, and soils of the Sierra Nevada from approximately 12,000 YBP to present. The figure indicates only general patterns of change and qualitative measures of conditions (e.g., moister) are relative only to previous and later conditions in the Sierra Nevada. Climate, dominant vegetation, vegetation structure, and charcoal information are interpreted from available information. The soils time line labelled "Lake" is based on cores of lake sediments (Edlund and Byrne 1991) and the time-line labelled "Meadow" is based on cores of meadow sediments (Anderson and Smith 1994).

Soils. — The retreat of the glaciers left surface deposits of glacial flour, sands, and silts (Fig. 1). Subsequent soil development varied but, in general, soils until around 10,000 YBP were largely gravels, silts, and sand, followed by layers with increasing organic content. Soils since 10,000 YBP have varied in organic content with the interruption of a distinct volcanic ash layer about 7,000 YBP (Anderson and Carpenter 1991, Edlund and Byrne 1991).

In meadows on the west slopes of the Sierra Nevada, Anderson and Smith (1994) found soils of 9,000 to 10,000+ YBP were composed primarily of gravels and medium to coarse grain sands with little organic material. These soils were followed by silts and sands, containing much larger concentrations of organic material from ~4,500 to 3,000 YBP. Since then, meadow soils have largely been considered to be peat.

Vegetation Composition and Structure. — Vegetation composition following the late Pleistocene, changed in response to shifts in climate (Fig. 1). Following the retreat of the ice in the Sierra Nevada, 12,000-15,000 YBP, vegetation was dominated by species characteristic of dry conditions, including sagebrush (*Artemisia* spp.), juniper (*Juniperus* spp.), and pine (*Pinus* spp.). As the climate became moister, lodgepole pine (*Pinus contorta*) and white fir increased in dominance. When temperatures increased and effective precipitation declined, from around 3,000 to 9,000 YBP, pines declined slightly and oaks (*Quercus* spp.) and bracken fern (*Pteridium* spp.) increased. From 3,000 to 4,500 YBP, when temperatures cooled and moisture increased, the forest vegetation compositions were more similar to those of today and include the highest incidence of fir (*Abies* spp.) and high amounts of cedar (*Calocedrus* spp.) and pine (Davis et al. 1985, Anderson and Davis 1988, Anderson 1990, Edlund and Byrne 1991, Anderson 1994).

Forest ecosystems are often perceived as communities of plant species that persist together in space and through long periods of time. However, vegetation assemblages with no modern analogues existed for some time in the Holocene (Davis 1981, Foster et al. 1990, Whitlock 1992). Entire vegetation assemblages did not always respond to climate change by simply moving up or down slopes or latitudinally. Rather, these entities assembled by chance as the various species responded individually to changes in environmental variables (Brubaker 1988, Huntley and Webb 1989, West 1990).

As species composition of the forests changed, their structure also varied through the Holocene (Fig. 1). Vegetation immediately following the ice retreat was relatively open and dominated by shrubs and smaller trees, characteristic of areas of cool, dry conditions. The forest canopy was more closed when climates were cooler and moister and more open when climates were warmer and drier.

Treeline. — The treeline, the upper elevational limits of persistent trees, in the southern Sierra Nevada varied from about 65 m above to 10 m below the present treeline at five distinct elevations over the last 6,000 years. The treeline remained at about 65 m above present treeline for about 3000 years prior to 3400 YBP. About 3200 to 3400 YBP, the treeline moved downslope some 30 m to between 30 and 37 m above present treeline. From 1300 to 1400 YBP, the treeline declined to 10 m below today's level. Finally, starting about 850 to 950 YBP, treeline rose some 10 m to the present level. Establishment of small trees above the present treeline in the last 100 years suggests that treeline is continuing to rise (Scuderi 1987).

Fire and Charcoal. — Deposits of sedimentary charcoal in lake beds are indications of wildfire events (Fig. 1). Coarser charcoal particles may be useful indicators of more local fire events; the degree of locality depends on the drainage patterns of the lake or meadow cored (Clark 1988). The greatest amounts, of both small and large charcoal particles was deposited in the Sierra Nevada between about 7,000 and 10,000 YBP, with apparent peaks between 2000 and 3000 YBP and 4000 and 6000 YBP (Davis et al. 1985, Davis and Moratto 1988, Edlund and Byrne 1991). A more recent influx of charcoal was found at about 600-700 years B.P (Anderson and Carpenter 1991). This concentration of charcoal suggests a long period with either frequent or large fire events.

Wildlife. — Little information exists about the association of wildlife with ecological changes in the Sierra Nevada. Some information regarding the variety of large mammals exists from fossils of the late Pleistocene from the San Francisco Bay area of Central California and from locations to the east in the Great Basin. This record includes a variety of taxa that no longer exist in the areas studied, and were probably lost in the late Pleistocene, such as mastodons (*Mammut* spp.), mammoths (*Mammuthus* spp.), ground sloths (*Megalonyx* spp., *Paramylodon* spp., and *Nothrotherium* spp.), tapirs (*Tapirus* spp.), camels (*Camelops* spp. and *Hemiauchenia* spp.). It also includes taxa that presumably were found in the Sierra Nevada and currently persist within California such as elk (*Cervus* spp.), deer (*Odocoileus* spp.), and pronghorn (*Antilocapra* spp.) (Edwards 1992, Grayson 1993). Such a diversity of large grazing and browsing animals depended on grasses and shrubs.

Information on some smaller species is available for the Holocene in the Great Basin. The fauna includes pikas (*Ochotona* spp.), cottontails (*Sylvilagus* spp.), voles

(*Microtus* spp.), and woodrats (*Neotoma* spp.), (Grayson 1993).

Sierra Nevada in the Past Millennium

Precipitation. — Effective precipitation, estimated for California using tree-ring analyses (Fritts et al. 1979, Fritts and Gordon 1980), has varied widely from 1600 to the present (Fig. 2). The years from 1600 to 1900 were appreciably drier and cooler (Graumlich 1993) than then in the Twentieth Century. About 70 years in the seventeenth century, 90 years in the eighteenth century, and 75 years in the nineteenth century were drier than the average recorded from 1901 to 1970. The increasing moisture in the Sierra Nevada appears to have begun in the late 1800s and continued into the mid 1900s but this period did include severe drought years. Only two centuries in the last 2000 years have had fewer severe drought years than the 100 years from 1851 to 1950 (Hughes and Brown 1992).

Water Levels. — The water level of Mono Lake has varied considerable in recent time. In 1857, the surface level of Mono Lake was measured at 1,952.76 m elevation (Stine 1981) and the lake level increased 6.4 m, reflecting the heavier precipitation of the period, until 1919 when it was measured at 1,959.16 m elevation (Fritts et al. 1979, Fritts and Gordon 1980, Stine 1991). After 1920, the surface level of Mono Lake has declined to 1,955.81 m elevation in November 1940 when Los Angeles Department of Water and Power began its diversions (Stine 1981).

The presence of submerged, relict stumps at four lakes and rivers in the Sierra Nevada, and adjacent areas, indicate there were at least two periods of severe, extended drought ending in mid-700 and the early 900s YBP. The droughts reduced lake levels to permit establishment of lodgepole pine, Jeffrey pine, black cottonwood (*Populus balsamifera trichocarpa*), rubber rabbitbrush (*Chrysothamnus nauseosus*), and big sagebrush (*Artemisia tridentata*) within contemporary lake margins; remnants of the stumps presently stand under 8 to 19 m of water. The drought periods permitted persistence of trees and shrubs for relatively long periods; two lodgepole pine stumps from Tenaya Lake were aged at 68 and 141 years (Stine 1994).

Fire Frequency and Climate. — Fire frequencies, indicated by fire scars in five disjunct giant sequoia (*Sequoia giganteum*) groves, were quite low from about 1,200-1,500 YBP but generally increased after about 1,200 YBP. Fire frequencies were greatest in all but one grove from about 700-1,000 YBP. Decline in fire frequency was general following 700 YBP (Davis et al. 1985, Swetnam 1993) but there were episodes of increased fire frequencies for some groves 300-400 YBP. When fire frequencies were low, the longest periods without recorded fires ranged from 15-30 years. But, when fire frequencies were high, the longest periods without recorded fires were less than 13 years (Swetnam 1993).

The fire frequency patterns observed are best explained by variations of precipitation and temperature. Years when fires were recorded in all groves were relatively dry, and those when fires were not recorded in any groves were relatively wet. Higher growing season temperatures resulted in higher numbers of fires. Precipitation was most closely related to short-term fire patterns at small geographic scales whereas temperatures were more closely related to longer-term fire patterns at decade and century scales (Swetnam 1993).

When fires were most frequent they appear to have been small, patchy, and discontinuous. During periods of less frequent fires, they appear to have been larger and generally more continuous. The evidence indicates these later fires burned during regional events similar to the 1987 wildfires as they were synchronous over the widely separate groves (Swetnam 1993).

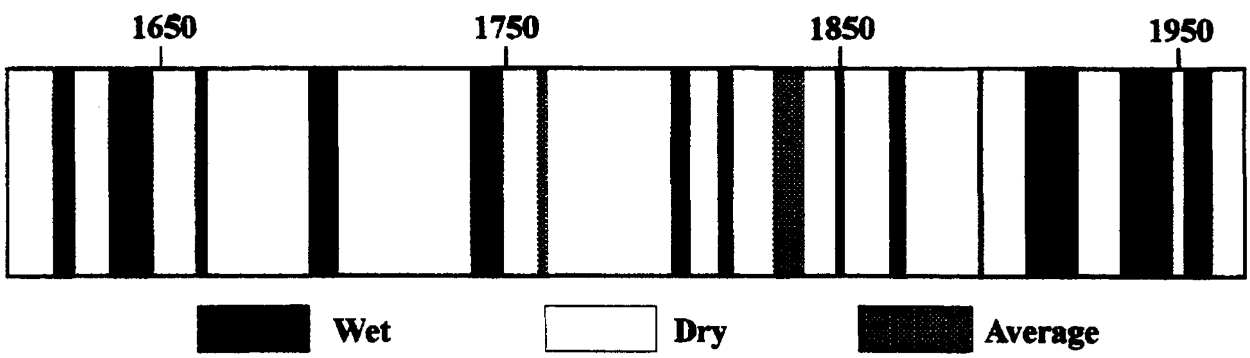

Fig. 2. Precipitation for the Sierra Nevada from 1600 to present. Average precipitation is based on the mean of the observed precipitation from 1901 to 1970.

Sierra Nevada at the Time of European Contact

Historical photographs and information from forests that are currently undergoing relatively frequent disturbances suggest that "average" characteristics of forests, especially ponderosa pine and mixed conifer, at the time of European settlement of the Sierra Nevada, was more open than today (Gruell 1994). Crown closure was more open, number of stems was much lower, and there was a much higher proportion of large diameter trees (diameter at breast height > 0.6 m). Shrubs, while they appear to be numerous, were generally not decadent and grasses were more abundant. These characteristics describe "average" conditions of the landscape. Areas with dense crown cover, with smaller densities of large diameter trees, or with very abundant and decadent shrubs undoubtedly existed. But we do not yet have an understanding of the spatio-temporal distribution patterns of different vegetation structures and compositions across the Sierra Nevada.

The spatial and vertical structural patterns that existed in these forests are the result of a variety of disturbances, operating at different intensities and spatio-temporal scales, causing mortality and influencing regeneration. Specific disturbances include occasional lightning strikes killing individual trees; bark beetles, other insects and diseases that attack single or groups of trees; and fires that burn with varying severity across this patchy landscape.

Wildlife. — The wildlife fauna at European contact is better documented but the information is quite scattered and a thorough treatment is beyond the scope of this paper. The large mammal fauna was heavily impacted starting in the 1840s by subsistence and later market hunting as well by the alterations made to their habitats. Although much of the large mammal fauna encountered was in the Central Valley and the lower foothills, many animals, especially deer and bighorn sheep (*Ovis* spp.), were taken higher in the Sierra Nevada. Around Fort Tejon in the Tehachapi Mountains, Xántus collected vertebrate specimens for the Smithsonian Institution in the late 1850s. He reports encountering or collecting a variety of wildife including many reptiles, birds, ground squirrels (*Spermophilus* spp.), coyotes (*Canis latrans*), foxes (*Vulpes macrotis* and *Urocyon cinereoargenteus*), bobcats (*Felis rufus*), and bighorn sheep (*Ovis canadensis*) (Zwinger 1986). In the foothills or on the edge of the Central Valley, Brewer, in the early 1860s, encountered rattlesnakes (*Crotalus* spp.), coyotes, and antelope (= pronghorn (*Antilocapra americana*)). He also encountered rattlesnakes, grouse (~ *Dendragapus obscurus*), deer, and bear (species not indicated) at higher elevations (Farquhar 1966).

FOCUS OF ECOSYSTEM MANAGEMENT

In the past 12,000 years, climate, soils, and fire regimes in the Sierra Nevada have changed considerably causing variation in forest composition and structure. Although the general temporal patterns of ecosystem variation are becoming clearer, the spatial variation in vegetation characteristics, disturbance regimes, and vegetation growth patterns across the Sierra Nevada at specific times remain largely unknown. We still need to learn about the geographical extent of the different compositions and structures of vegetation, where on the landscape these particular mixes of vegetation occurred, and the sizes and shapes of the different patches of vegetation. Resolution of these questions will permit a better understanding of spatio-temporal arrangements of landscape pattern and function, and will provide a firmer footing for implementation of ecosystem management. However, this information will not be developed overnight and management decisions will need to be made in the interim.

We are not able to predict future climatic conditions or how the conditions will influence future forest composition and structure. If the record of the past is any indication, future conditions are more likely to be drier than they have been in the twentieth century. The current wave of massive tree mortality suggests that many of the existing forest compositions and structures, that developed under a slightly different climatic regime earlier in this century, cannot be perpetuated under current climatic conditions.

Under such a scenerio, management toward a forest reflecting drier conditions seems to be a prudent course of action. Such a forest would have fewer trees but a proportionally larger number of larger diameter trees (in excess of 24 in. in diameter). In areas dominated by mixed conifer and ponderosa pine, the number of white fir stems should be reduced. Periodic fire in suitable areas, after reducing the current fuel loadings and ladders, will help maintain this system and should help establish, improve, and maintain the herbaceous undergrowth that is currently absent from many forested areas in the Sierra Nevada.

CONCLUSIONS

Since at least the end of the last glacial period, the ecosystems of the Sierra Nevada have changed continuously. Vegetation distribution, composition, and structure has exhibited extensive variation in space and time. A goal of ecosystem management should be to manage so as to achieve the variety of conditions produced by the inherent ecological processes and resulting patterns, rather than attempting to manage so as to achieve some easy-to-implement 'generalized' condition. Interpretations of causes of perceived trends in vegetation composition and structure must be made cautiously. Much of the cause of the change of forest condition between the presettlement Sierra Nevada and today is attributed to human activities, including livestock grazing, timber harvest, and fire suppression. Although these activities have undoubtedly affected the forest and its rate of change, much of the Twentieth Century in California was very moist and relatively warm. Under such a different climatic regime, in the absence of the human activities mentioned above, the begetation may have changed in the direction observed but not to the magnitude seen today. Ecosystem management in the Sierra Nevada should be predicated on the characteristics of forests persisting under drier conditions and management objectives for patterns of vegetation composition and structure should largely reflect patterns of disturbances under these conditions.

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