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U.S. Geological Survey
Western Ecological Research Center

Sierra Nevada Global Change Research Program

Sierra Nevada Forest Dynamics: Pattern, Pace, and Mechanisms of Change

Annual Report for Fiscal Year 1999

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EXECUTIVE SUMMARY

The Sierra Nevada Global Change Research Program began in 1991 as a peer-reviewed, competitively-funded component of the National Park Service's (now USGS-BRD's) Global Change Research Program. While Sequoia, Kings Canyon, and Yosemite national parks form the core study areas of the program, the full study region encompasses adjacent public lands.

The goal of the Sierra Nevada Global Change Research Program is to understand and predict the effects of global changes on montane forests. By far the greatest limitation to understanding and predicting the effects of future global changes is the lack of a precise mechanistic understanding of how contemporary forest structure and function are controlled by the physical environment, disturbances, and biotic processes. Our research program therefore places landscape patterns within the context of the physical template (abiotic factors such as climate and soils), disturbances (such as fire), and biotic processes (demography, dispersal, growth, and competition). Our program focusses on developing a mechanistic understanding of this simple model as it applies to Sierra Nevada forests in particular, but also for the montane forests of western North America in general.

Our program consists of integrated studies organized around three themes: paleoecology, contemporary ecology, and modeling. The *paleoecological theme* takes advantage of the Sierra Nevada’s rich endowment of tree-ring and palynological resources to develop an understanding of past climatic changes and the consequent responses of fire regimes and forests. The *contemporary ecology theme* takes advantage of the Sierra Nevada's substantive climatic gradients as “natural experiments,” allowing us to evaluate climatic mechanisms controlling forest composition, structure, and dynamics. The *modeling theme* integrates findings from the paleoecological and contemporary studies, and is the indispensable vehicle for scaling up our mechanistic findings to regional landscapes, and predicting which parts of montane landscapes may be most sensitive to future environmental changes.

The Sierra Nevada Global Change Research Program currently focusses on addressing nine central sets of questions:

- What is the relative importance of topography and soil on site water balance in the Sierra Nevada, and how well does this compare with model predictions?
- What is the role and importance of reproduction in determining forest pattern and forest sensitivity to climatic change? By what mechanisms does climate control reproduction, and therefore forest sensitivity to climatic change?
- How do seed dispersal, seedling dynamics, and fine-scale variations in topography and soils interact with climatic change to affect forest sensitivity and change at local scales?
- How does climatic change affect the spatial extent, landscape pattern, and severity of fires?
- What are the relative importances of tree recruitment, death, and growth rates, and their interannual variabilities, in determining forest response to climatic variation in space and time?

- What portions of Sierra Nevada landscapes are most sensitive to climatic changes (temperature, precipitation, and seasonality), what are the implications of this for a greenhouse world, and what are the implications for land managers?
- Does climate synchronize fire regimes at subcontinental scales? If so, what large-scale climatic phenomena drive the synchrony?
- Can agents of pattern formation and mechanisms of forest change be generalized at subcontinental scales?
- How do the relative importances of agents of pattern formation vary among different climates? Is our understanding of mechanisms of forest change sufficient for a single model to explain forest dynamics at several different sites across the continent?

In 1999, substantial progress was made in addressing each of these questions. For example, within our established long-term forest dynamics plots arrayed along a climatic (elevational) gradient, 47 new 25×25 m seedling dynamics quadrats were established, in which the fates of tens of thousands of tree seedlings will be followed annually for at least the next four years. Fire-scar chronology networks were compared among the southwestern U.S., the Sierra Nevada, the Blue Mountains in Oregon, and the Cascades in Washington, revealing climatically-driven periods of asynchrony among fire regimes of the Pacific Southwest and Pacific Northwest. In a paper accepted in *Ecological Applications*, computer simulations were used to determine which portions of the southern Sierra Nevada landscape are most sensitive to climatic change, and how this knowledge can be applied by managers to design monitoring programs. Additionally, the Sierra Nevada global change staff worked with the other USGS-BRD global change programs within the Western Mountain Initiative (Olympic, Glacier, and Colorado Rockies) to map out a series of collaborations meant to draw broad generalizations about the effects of global changes on mountain ecosystems.

In 1999 we published, or had accepted for publication, twenty-eight scientific manuscripts (including one Ph.D. dissertation) related to the Sierra Nevada Global Change Research Program. A comparable number of talks and poster presentations were given at universities, professional meetings, and agency workshops.

The Sierra Nevada Global Change Research Program initiated new partnerships and continued old ones. After ten years of collaboration, our principal investigators at Duke University, Montana State University, and the University of Arizona continue to be an integral and indispensable part of our team. Additionally, principal investigators worked toward common goals with scientists from the University of California, University of Washington, Oregon State University, U.S. Forest Service, and the National Park Service. Our staff also focussed on outreach and technical assistance. We were interviewed by newspapers and television crews; gave presentations to governmental, university, and school groups; and provided extensive technical assistance to the National Park Service, such as by developing goals for fire management programs, assisting in preparation of fire and natural resources management plans, training park staff, and designing monitoring programs.

Besides continuing research, data analysis, and manuscript preparation that addresses the nine central questions listed above, fiscal year 2000 will see a major push toward drafting a book that integrates and synthesizes results to date of the Sierra Nevada Global Change Research Program.

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INTRODUCTION

The Sierra Nevada Global Change Research Program began in 1991 as a peer-reviewed, competitively-funded component of the National Park Service's (now USGS-BRD's) Global Change Research Program (Stephenson and Parsons 1993). While Sequoia, Kings Canyon and Yosemite national parks form the core study areas, the full study region encompasses adjacent federal and state lands, and stretches from north of Yosemite to the southern end of the range, from the San Joaquin Valley in the west to the Owens Valley in the east (Fig. 1).

The goal of the Sierra Nevada Global Change Research Program is to understand and predict the effects of global changes on montane forests. Forests provide humanity with economically important and often irreplaceable ecosystem products and services, such as watersheds, wood, fiber, biodiversity, and recreational opportunities. Ongoing global changes have potentially far-reaching effects on these products and services, and hence on society. Land-use change (an increasingly important form of global change) already has affected the health and resilience of many forests, leading to controversy on how best to counteract the changes (e.g., Stephenson 1999). Additionally, forests sequester the majority of the terrestrial biosphere's carbon (Kirschbaum et al. 1996), making them key components of the global carbon cycle and key contributors of biogenic feedbacks to global climatic change (Melillo et al. 1996). For these and other reasons, the Intergovernmental Panel on Climatic Change has identified a mechanistic understanding of forest responses to climatic change as a high priority for research.

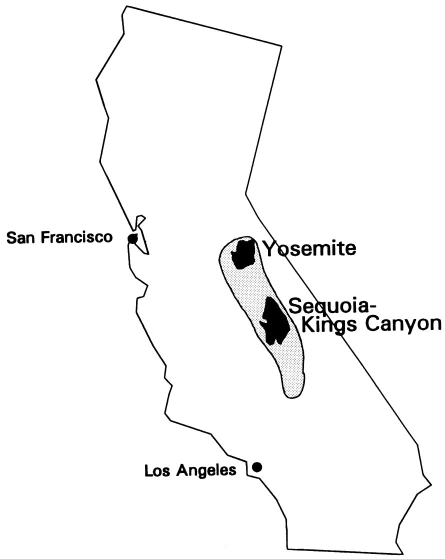

Figure 1. Locations of study areas within California.

CONCEPTUAL APPROACH

By far the greatest limitation to understanding and predicting the effects of future global changes is the lack of a precise mechanistic understanding of how contemporary forest structure and function are controlled by the physical environment, disturbances, and biotic processes. Our research program therefore places landscape patterns within the context of the physical template (abiotic factors such as climate and soils), disturbances (such as fire), and biotic processes (demography, dispersal, growth, and competition) (Fig. 2). Our program focusses on developing a mechanistic understanding of this simple model as it applies to Sierra Nevada forests in particular, but also for the montane forests of western North America in general.

The task of gaining a mechanistic understanding of forest dynamics is beset with notoriously severe problems. Most of these problems result from the great spatial and temporal scales encompassed by forest dynamics, which often preclude many forms of experimental manipulation. As a consequence, most researchers attempting to predict the consequences of global changes on forests have relied on computer models. However, predictions from computer models are only as good as the assumptions that drive them, and these are often untested and unrealistic (e.g., Loehle and LeBlanc 1996).

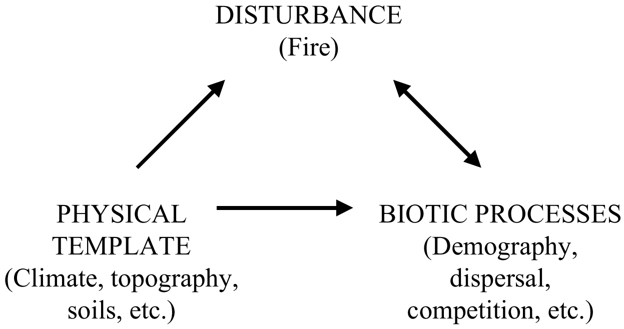

Figure 2. Agents of pattern formation

We have sought to overcome these problems through integrated studies organized around three themes: paleoecology, contemporary ecology, and modeling. All three consider the role of the physical template and disturbance in controlling biotic processes and responses.

Paleoecological theme

The paleoecological theme focusses on understanding past climatic changes and the consequent responses of fire regimes and forests. The Sierra Nevada is endowed with an extraordinarily rich record of such changes. The region is unique worldwide in having at least four tree species from which multi-millennial tree-ring chronologies of climatic change can be derived (e.g., Hughes and Brown 1992, Graumlich 1993, Hughes and Graumlich 1996, Garfin 1998). Fire scars within giant sequoia tree-rings contain annual- and seasonal-resolution fire histories spanning the last several millennia, revealing a strong link between changing climate and fire regimes (Swetnam 1993). Additionally, charcoal trapped in meadow sediment documents changes in fire regimes spanning the entire Holocene (Anderson and Smith 1997). Biotic response to changing climate and fire regimes are recorded in the age structures of existing forests and in the woody remnants of past forests (Stephenson 1994, Lloyd and Graumlich 1997), and in Holocene-length records of pollen trapped in meadow sediments (Anderson and Smith 1994).

Contemporary ecology theme

The contemporary ecology theme takes advantage of the Sierra Nevada's substantive climatic gradients as “natural experiments,” allowing us to evaluate climatic mechanisms controlling forest composition, structure, and dynamics (e.g., Halpin 1995, Kern 1996, Stephenson 1998, Stephenson et al. 1998 and *in prep.*). A fortuitous combination of extreme environmental gradients and physiographic complexity makes the Sierra Nevada mountain range an ideal laboratory for such an approach. Elevation rises from near sea level to 4,418 m in less than 100 km horizontal distance -- one of the most extreme elevational gradients in temperate North America. A steep temperature gradient -- from warm mediterranean to cold alpine -- parallels the elevational gradient, and in turn, is overlain by a gradient of decreasing precipitation from west to east. These climatic gradients combine with highly variable soils and topography to create a physical template that includes an extraordinary range of local site water balances (Stephenson 1998).

Modeling theme

The modeling theme integrates findings from the paleoecological and contemporary studies, which, of necessity, are conducted at local spatial scales. Modeling is the indispensable vehicle for scaling up our mechanistic findings to regional landscapes, and is the key to predicting which parts of montane landscapes may be most sensitive to future environmental changes (e.g., Urban 2000).

Importantly, our research program seeks to generalize its findings beyond the Sierra Nevada. To this end, we are collaborating with several ongoing research efforts elsewhere in western North America. Much of our external collaboration is with three other global change research programs within the USGS-BRD's Western Mountain Initiative: Olympic, Glacier, and Colorado Rockies (see the Western Mountain Initiative web site at *http://www.nrel.colostate.edu/brd_global_change/theme_mountain.html*). Other collaborations are listed later in this document.

RESULTS OF PREVIOUS WORK

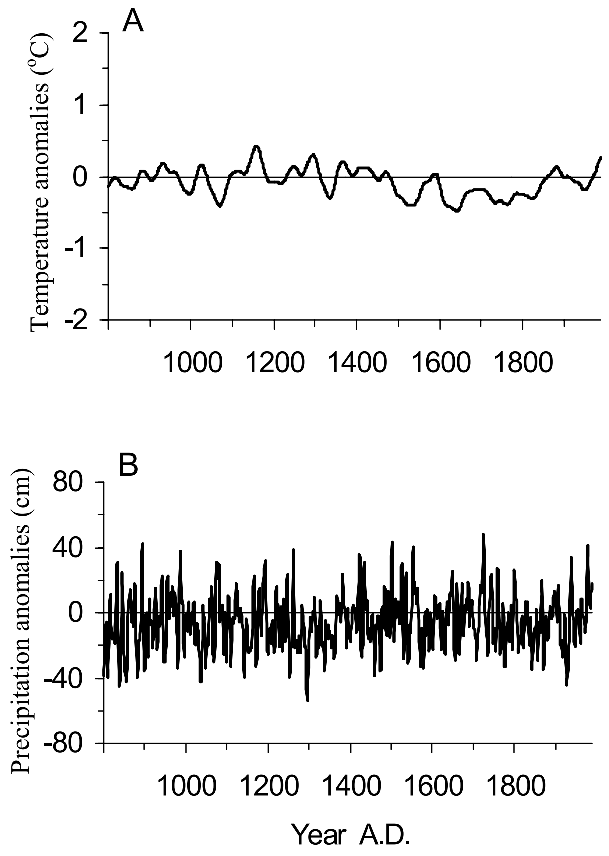

Figure 3. Tree ring reconstructions of (A) past temperature and (B) precipitation in the Sierra Nevada. From Graumlich (1993).

The Sierra Nevada Global Change Research Program has leveraged its funds by collaborating with more than 20 scientists from 10 universities and research organizations, contributing to more than 160 publications and abstracts since 1991, including six M.S. and seven Ph.D. theses (see our web page and full bibliography at *http://www.werc.usgs.gov/sngc/*).

Integration of our past work is facilitated by considering results within the context of the physical template, disturbance, and biotic processes (Fig. 2), and evaluating their contributions to our understanding at scales from forest stands to landscapes and regions. Hughes and Graumlich's (1996) 8000-year climatic reconstruction for the Sierra Nevada reveals that the warmth of the 20th Century has been experienced most recently during the 12th and 14th centuries AD (Graumlich 1993) (Fig. 3). A sobering feature of these records is the documentation of regular multi-decadal droughts, of much greater length and severity than any experienced in the last 100 years. At a regional scale, these droughts are predictable from subcontinental-scale atmospheric anomalies over the Pacific and Western North America, and can be tied to tree growth anomalies (Garfin 1998).

Our paleoecological records also provide insights into climatic, anthropogenic, and topographic controls of disturbance regimes, particularly fire. A sharp peak in charcoal deposition in montane Sierra Nevada meadows is evident in the early Holocene (ca. 9000 years ago), followed by millennia of low charcoal deposition (Anderson and Smith 1997). Charcoal deposition has increased again for about the last 4500 years. The latter increase corresponds to changes in forest composition (Anderson and Smith 1994). Sierra Nevada forests also have produced one of the longest and best-replicated networks of tree-ring based fire-history reconstructions in the world (Swetnam et al. 1992, Swetnam 1993, Caprio and Swetnam 1995, Swetnam et al. in prep.). Swetnam's >2000 year annual- and seasonal-resolution fire-scar chronologies from sequoia groves demonstrate substantial variation in fire frequency and size across all temporal and spatial scales (Fig. 4). Before about 1850, predominantly low- to moderate-intensity surface fires burned within portions of any given sequoia grove, on average, about every 3 to 8 years, but of particular note is the occurrence of occasional high-intensity fires. With the demise of Native Americans, introduction of livestock grazing, and suppression of lightning fires following Euroamerican settlement, most grove areas have experienced a 100- to 130-year period without fire -- a fire-free period that is unprecedented over at least the last several millennia. Fifty-five additional fire-scar chronologies have been developed along four elevational transects, greatly extending the elevational range of fire-scar chronologies. Fire frequencies along these transects are strongly and negatively correlated with elevation, demonstrating a strong link between climate and fire regimes (Swetnam et al. 1998). Fire chronologies from both sequoia groves and the elevational transects were highly synchronous across temporal scales of years to decades. Moreover, these synchronous patterns were well-correlated with climatic changes inferred from the other tree-ring studies (see the preceding

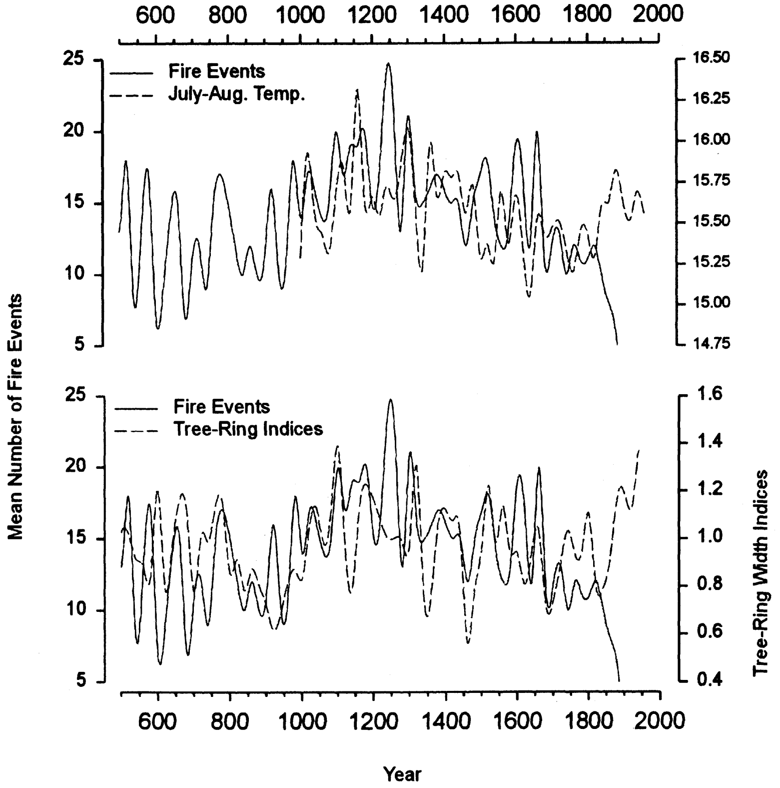

Figure 4. The past relationship between temperature and fire frequencies in the Sierra Nevada as determined by dendrochronological records. From Swetnam 1993.

paragraph). Variations in giant sequoia fire regimes generally corresponded with century-scale climatic episodes (high fire frequencies during the Medieval Warm Period, and low fire frequencies during the Little Ice Age).

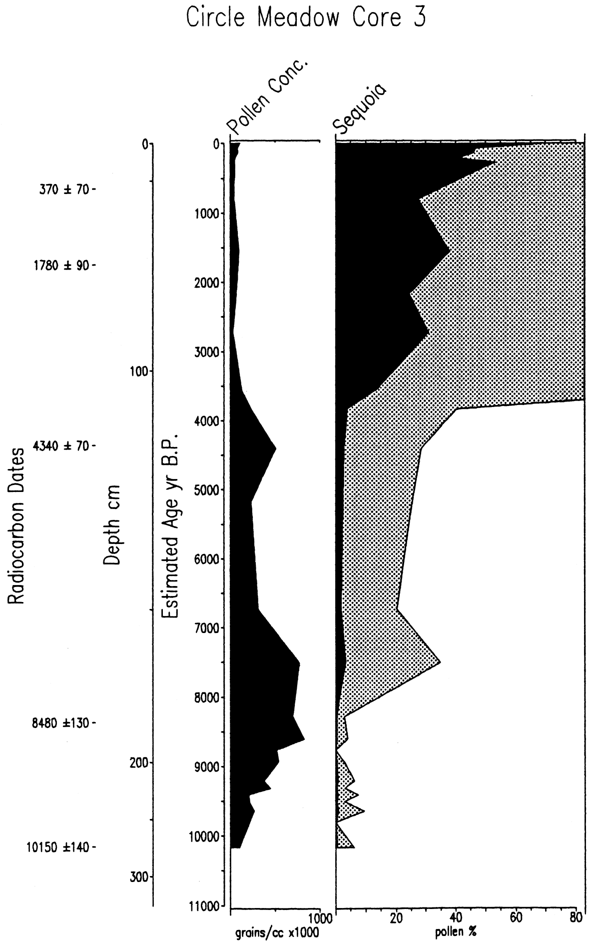

Figure 5. Pollen records of the past abundance of giant sequoia in the Giant Forest, Sequoia National Park. From Anderson and Smith 1994.

The strong linkage between climate, disturbance, and vegetation is illustrated in pollen records. Within present sequoia grove boundaries, sequoias (and firs) began to increase dramatically in importance relative to pines about 4500 years ago (Fig. 5), coincident with a slight global cooling and an increase in charcoal deposition (Anderson 1994, Anderson and Smith 1994, Anderson and Smith 1997). While we have clearly demonstrated that climate and fire regimes have varied -- sometimes substantially -- within sequoia groves during the last few millennia, the combined effect on giant sequoia populations in large groves, as demonstrated by age-structure studies, has been only moderate (Stephenson 1994 and in prep.). Land use change has had a greater effect on forests than several millennia of climatic and fire change; that is, the greatest anomaly in sequoia regeneration over at least the last two millennia has been a nearly complete regeneration failure attributable to modern fire exclusion (Stephenson 1994 and in prep.).

Treeline forests, in contrast to giant sequoia populations, have responded more strongly to climatic changes and, unlike treeline dynamics elsewhere in the world, Sierra Nevada treelines are controlled by both temperature and precipitation (Lloyd and Graumlich 1997 -- this work was given the Ecological Society of America's Cooper Award in 1998). Remnant wood up to 60 vertical meters above current treeline is testimony to the fact that 20th century climatic variability in the Sierra Nevada has yet to exceed the bounds of climatic variability over the past 3500 years.

Across scales from local Sierra Nevada forest stands to continents, water balance equations have been used successfully to explain vegetation distribution (Stephenson 1990, 1998) (Fig. 6). Factors that affect site water availability (e.g., soil depth) and evaporative demand (e.g., slope aspect) have intrinsically different effects on site water balances (Stephenson 1998).

These differences are evident in forest patterns. Spatial hydrology (e.g., topographic convergence, lateral hydrologic fluxes) represents an additional parameter with predictive power for explaining forest distribution (Halpin 1995). Tree death rates increase sharply with decreasing elevation (i.e., increasing temperature) (Stephenson et al. 1998, and in prep.). The increase in death rates is independent of stand structure and composition and is driven by a dramatic increase in death by biotic factors (insects and fungi) with decreasing elevation, thus indicating a potential linkage between climate (in this case temperature) and biotic interactions. Forest carbon turnover, both absolute and relative, increased with decreasing elevation (increasing temperature) (Stephenson et al. in prep.).

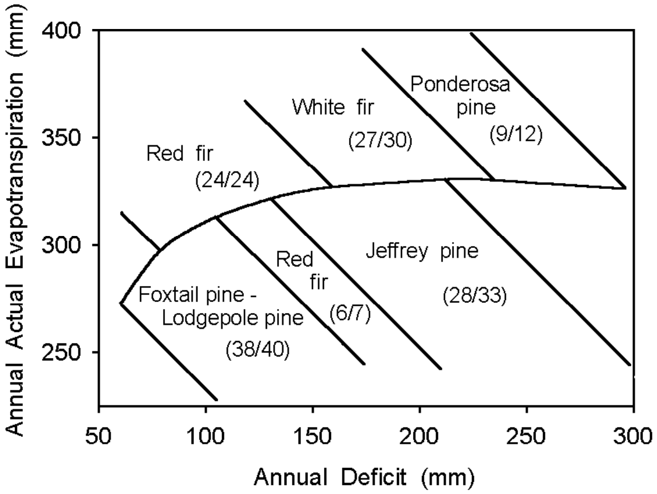

Figure 6. Forest types of the Sierra Nevada in relation to actual evapotranspiration and water deficit. From Stephenson 1998.

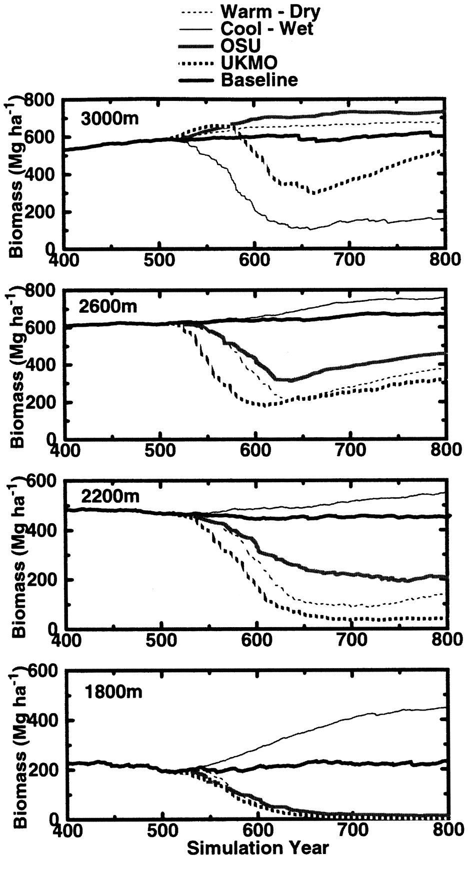

Figure 7. Total woody biomass simulated at four elevations for four climatic change scenarios and baseline conditions using ZELIG. From Miller and Urban 1999.

Modern fire regimes depend heavily upon rate of fuel accumulation and this is reflected in annual accumulation differences between ponderosa pine and white fir stands (van Wagtendonk et al. 1998a, 1998b). FARSITE, a user-friendly Windows-based fire area simulator, was initiated as part of the Sierra Nevada Global Change Research Program and is currently the most widely used tool for planning prescribed fires and predicting the behavior of wildfires (Finney 1995, 1998).

The Zelig gap model (version Facet) acts as an integrative framework for coupling physical template, disturbance, and biotic processes, and is validated with both historical and contemporary forest and climate reconstructions (Fig. 7). It can be successfully scaled up (MetaFor) to replicate actual distributions of Sierra Nevada tree species along elevational gradients (Urban et al. 1999 and in press). This model corroborates Stephenson (1998) by predicting fundamentally different effects of water availability and evaporative demand on site water balances (Urban et al. in press).

We have also emphasized the radically different natural scaling of factors affecting site water balances, e.g., precipitation and temperature that vary over hundreds of meters in elevation, while soil depth varies over centimeters (Urban et al. in press). Further, some of these factors (temperature, precipitation) vary considerably through time and might be expected to change under greenhouse scenarios; by contrast other important factors (soil texture, depth, and microtopography) vary principally over space and are less likely to change under greenhouse scenarios. This distinction is important for global change research as most previous work has focused largely on temperature and precipitation, whereas our work suggests that other factors (especially soils and microtopography) are at least as important to the water balance and ecosystem response.

Our goal in modeling fire has been to reproduce the statistics of the Sierra Nevada fire regime, based on actual mechanistic processes that couple climate, forests, and fire. This is in contrast to other modeling approaches that “feed” the model fire statistics (e.g., mean fire size, frequency) as input parameters. Based on first principles (such as modeled fuel accumulation, water content, and continuity), Zelig successfully reproduces the observed paleoecological record of fire frequencies across the elevational gradient (Miller 1998, Miller and Urban 1999a-c). Further analysis of the model reveals that lower-elevation fires are constrained by anomalous wet years (which accelerate fuel accumulation), while high-elevation fires are constrained by anomalous dry years (which are critical to lowering fuel moisture). These findings are supported by our paleoecological reconstructions of fire regimes (Swetnam et al. 1998). Thus, the fire regime is driven by both the mean and variance in climate, but the direction of this variation itself changes with elevation.

We have placed strong emphasis on communicating the management implications and applications of our work. For example, Graumlich found that the last 50 years in California have been among the wettest of the last millennium, and that multi-decadal droughts of much greater length and severity than any experienced in California during the last century have occurred regularly in the past. These findings served as an abrupt wake-up call for California water resource planners, and received national attention. Swetnam's fire reconstructions are now used by land managers up and down the Sierra Nevada as a target for restoring pre-Euroamerican fire regimes. Stephenson's investigation of the effects of fire regimes on forest pattern and dynamics have led to modifications in both prescribed fire and timber harvesting approaches in the Sierra Nevada. Van Wagtendonk has provided an important tool to resource managers by the demonstrated use of basal area and live crown ratio to predict annual fuel increments for most Sierra Nevada trees. Finney's FARSITE fire behavior and spread model, initiated as part of our program, has become the most widely-used fire model by North American land managers. Miller and Urban have provided land managers with projections of the consequences of natural fire, prescribed fire, and timber harvest on Sierra Nevada forests. Urban's Zelig model also has proved to be an important tool for evaluating the impact of “unnatural” fuel accumulation on fire intensity and thus on stand structure.

RESEARCH QUESTIONS, 1999-2003

To emphasize the logic of our ongoing work and its relation to past work (described in the preceding section), we have categorized the research questions we are currently addressing (Table 1) according to spatial scale (vertical axis) and agents of pattern formation (horizontal axis).

TABLE 1.*	Physical template	Disturbance	Biotic processes	Models & integrative tools
Individuals & forest stands	**Question 1**		**Question 2**	**Question 3**
Sierra Nevada landscape		**Question 4**	**Question 5**	**Question 6**
Western Mountain region		**Question 7**	**Question 8**	**Question 9**

* For the time being, empty cells have been adequately addressed. Some questions have components in several cells.

Question 1: *What is the relative importance of topography and soil on site water balance in the Sierra Nevada, and how well does this compare with model predictions?* Two independent models suggest that local effects of soils and topography can profoundly alter site water balances in the Sierra Nevada, sometimes with an effect equivalent to a halving or doubling of regional precipitation. These models suggest that effects of slope aspect and soil water holding capacity on site water balance should be of comparable magnitude, but of fundamentally different effect on forest pattern (Fig. 8). Yet, actual forest patterns suggest that slope aspect may have much less effect than soil water holding capacity; that is, models predict that the elevation of a given forest type should be >500 m higher on a south-facing slope than on a north-facing slope, yet the observed difference is <200 m. Given the profound influence local conditions are likely to have on site sensitivity to climatic change (Urban et al. in press), it is important that we reconcile this apparent contradiction in order to have confidence in our model projections. To do so, we are gathering micro-

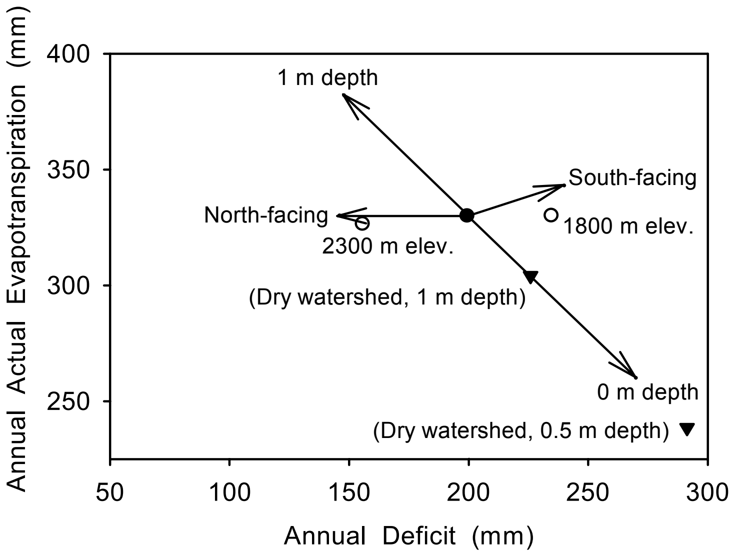

Figure 8. Effects of soil, topography and watershed on local site water balances. From Stephenson 1998.

meteorological and soil moisture data from a network of sites.

Question 2: *What is the role and importance of reproduction in determining forest pattern and forest sensitivity to climatic change? By what mechanisms does climate control reproduction, and therefore forest sensitivity to climatic change?* Forests are dominated by long-lived organisms that often exhibit inertia in their demographic response to change. Thus, there is a clear need to consider indicators that are likely to be sensitive to change, such as reproductive biology and growth rates. Of particular note here is the tantalizing suggestion from of our earlier research, that, in agreement with recent findings from eastern deciduous forests (Pacala et al. 1996), recruitment and death rates play a much greater role than growth rates in driving forest dynamics. This contradicts some of the basic assumptions of many forest dynamics models, and suggests that reproductive life history stages may be most sensitive to climatic change, and may ultimately drive forest change. As noted by Bennett (1998), seed dispersal and subsequent seedling establishment may be the most critical determinants of the rate of forest response to climatic change. Our permanent demography plots provide an opportunity for quantifying seed dispersal and seedling demography for the dominant species under a range of physical settings and biotic backgrounds.

Question 3: *How do seed dispersal, seedling dynamics, and fine-scale variations in topography and soils interact with climatic change to affect forest sensitivity and change at local scales?* To provide an integrative framework for understanding current forest conditions, investigate landscape sensitivity to future climate scenarios, and evaluate potential management options, we will incorporate the new results of field studies related to Question 2 into our forest dynamics models (Zelig and its derivatives).

Question 4: *How does climatic change affect the spatial extent, landscape pattern, and severity of fires?* Our modeling has made extensive use of our reconstructions of past fire frequencies along elevational gradients for conceptual development and for comparison with model outputs. Our models predict that, as climatic change affects fuels, ignitions, and fire spread patterns, there will also be changes in distribution of fire size and severity. Does the fire history record confirm the patterns and details of these model predictions? What can we learn about past fire sizes and severities from both modeling and tree-ring reconstructions that will aid managers in deciding upon ecologically appropriate prescribed fire characteristics under different climatic scenarios? Further feedback with the models requires more explicit spatial reconstructions of past fire regimes (and a greater range of sites represented) in relation to past climatic variation.

Question 5: *What are the relative importances of tree recruitment, death, and growth rates, and their interannual variabilities, in determining forest response to climatic variation in space and time?* Our research to date has suggested that recruitment and death rates play a much greater role than growth rates in driving forest dynamics. This contradicts some of the basic assumptions of many forest dynamics models. We are now working to verify our preliminary results by quantifying the relative importances of demographic rates and growth rates, on a species-by-species basis, for comparison with Zelig outputs and in a format useful for modifying the model, as needed.

Question 6: *What portions of Sierra Nevada landscapes are most sensitive to climatic changes (temperature, precipitation, and seasonality), what are the implications of this for a greenhouse world, and what are the implications for land managers?* While our earlier modeling efforts mostly were at the scale of forest stands (e.g., 0.1-10 ha), we will now scale up to landscapes (10,000-100,000 ha). Spatially-explicit models of landscape sensitivity can help land managers focus monitoring efforts on those areas most likely to respond to climatic change, and predict which portions of the landscape are highest priority for mitigation efforts.

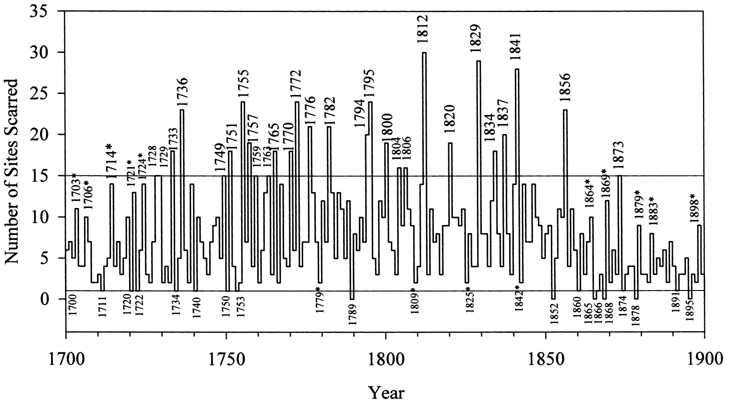

Figure 9. Time series of the number of Sierra Nevada sites recording a fire each year from 1700 to 1900. The largest and smallest fire years are labeled. From Swetnam et al. 1998.

Question 7: *Does climate synchronize fire regimes at subcontinental scales? If so, what large-scale climatic phenomena drive the synchrony?* One of the most interesting and important patterns from our earlier reconstructions of past Sierra Nevada fire regimes is fire synchrony over periods of several centuries and over vast landscapes (Fig. 9). Synchrony at these spatial and temporal scales is the hallmark of climatic influence. In addition to the Sierra Nevada and the Southwestern U.S. (Swetnam and Betancourt 1990, 1998), regional synchrony also has been reported by Dr. Thomas Veblen (*pers. comm.*) in the Colorado Rockies -- a result of global change research in BRD's broader Western Mountain Initiative. Regional synchrony is also suggested in Barrett et al.'s (1997) compilation of northern Rocky Mountain fire histories. We seek to identify *inter*-regional (sub-continental scale) fire synchrony, if any, and to determine the major atmospheric and oceanic phenomena driving it (e.g., the Aleutian Low, Great Basin High, Southern Oscillation, position and sinuosity of the jet stream, and dominant storm tracks). Such information, in addition to its immediate use by fire agencies wishing to predict the likely upcoming severity of fires in a given year, can be used with GCM output to predict future patterns of fire occurrence in western North America.

Question 8: *Can agents of pattern formation and mechanisms of forest change be generalized at subcontinental scales?* Based on our integrated models of paleoecology and contemporary forests, we are developing a detailed picture of the controls of forest structure, composition, and dynamics in the Sierra Nevada. How much overlap is there between our findings and those of other regions in western North America? We must address this if we are to draw broad generalizations on the effects of climatic change on montane forested ecosystems. To this end, we have formalized the coordination of efforts initiated by BRD's Western Mountain Initiative (*http://www.nrel.colostate.edu/brd_global_change/theme_mountain.html*).

Question 9: *How do the relative importances of agents of pattern formation vary among different climates? Is our understanding of mechanisms of forest change sufficient for a single model to explain forest dynamics at several different sites across the continent?* The relative importances of different agents of pattern formation are likely to differ among regional climates. For example, wet (energy-limited) forests will respond most strongly to temperature change, whereas dry (water-limited) forests will respond most strongly to precipitation change. Additionally, as increasing temperature converts energy-limited forests to water-limited forests, fire is likely to increase in importance as an agent of pattern formation. Understanding and prediction of forest response to significant climatic change requires models flexible enough to accurately model shifts in the relative importances of agents of pattern formation.

RESEARCH ACCOMPLISHMENTS, FISCAL YEAR 1999 AND PLANS FOR FISCAL YEAR 2000

Question 1: *What is the relative importance of topography and soil on site water balance in the Sierra Nevada, and how well does this compare with model predictions?*

Urban’s field crew established about 40 new georeferenced sample plots stratified within the Kaweah watershed, bringing their total to 99 samples over three years. Within each plot vegetation was sampled, tree growth rates measured, soil samples collected for lab analysis, and topographic variables were recorded. Urban’s crew also installed remote data-loggers within each of three of the global change program’s long-term forest demography plots: one each in low, mid, and high elevation forest. Each data logger recorded air and soil temperature, precipitation, and soil moisture at two depths on a continuous basis during the growing season. Urban’s graduate student (Ken Pierce) and the TECO field crew also established a network of about 24 HOBO temperature loggers, mostly in clusters of 3-4 loggers on contrasting slope facets at similar elevation. The goal is to use these data to develop regression-based methods of extrapolating temperature over complex terrain. Preliminary analyses of data from summer 1999 suggest that large-scale topographic features such as those governing cold air drainage may be more important that smaller-scale topographic features measured over 10's to 100's of meters.

In fiscal year 2000 we plan to re-install and maintain the remote data loggers across the elevational gradient, and to install about 20 longer-lasting temperature loggers this summer (HOBO pro's which will last a full year), focusing on larger-scale features of the Kaweah Basin.

Question 2: *What is the role and importance of reproduction in determining forest pattern and forest sensitivity to climatic change? By what mechanisms does climate control reproduction, and therefore forest sensitivity to climatic change?*

This was the initial year of this component of our program. In each of 22 of our long-term forest dynamics plots (see Question 5, below), at least two 25×25 m seedling dynamics quadrats were established, for a total of 47 quadrats (2.9 ha total). All seedlings <1.37 m tall were counted by size class, amounting to several tens of thousands of seedlings which, over the coming years, will be checked annually for growth and mortality. Additionally, a total of 415 seed traps (0.5×0.5 m) were established around the perimeters of the seedling quadrats; these will be emptied annually to determine variation in seed rain both through space (within plots and along the climatic gradient) and time (interannual climatic variation).

During Fiscal Year 2000, all plots will be re-censused, a thorough literature review of Sierra Nevada seed and seedling dynamics will be completed, and preliminary data analyses will be conducted. Additionally, we will initiate a parallel study of recruitment dynamics at two new treeline sites, one each in Yosemite (whitebark pine) and Sequoia-Kings Canyon (foxtail pine).

Question 3: *How do seed dispersal, seedling dynamics, and fine-scale variations in topography and soils interact with climatic change to affect forest sensitivity and change at local scales?*

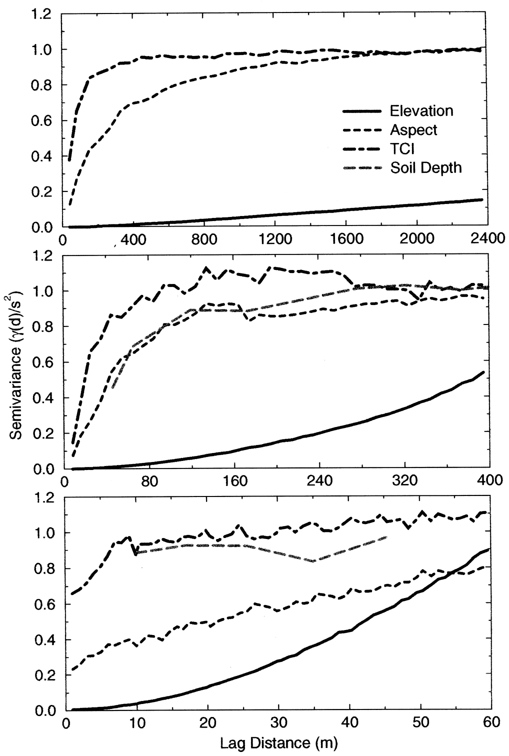

Figure 10. Spatial scaling, as semivariograms for elevation, aspect, topographic convergence, and soil depth at three scales. (top) The 90,000-ha Kaweah Basin in Sequoia National Park. (middle) The 50-ha Log Creek Watershed in the Kaweah Basin. (bottom) A 2.5-ha mixed conifer stand in the Log Creek Watershed. From Urban et al. (*in press*).

The fullest expression of this modeling effort must wait until we have several years of field data related to Questions 1 and 2, above. However, using data from earlier work by Dr. Pat Halpin in Sequoia National Park, we began to explore the latter part of the question (related to topography and soils) in a manuscript accepted for publication in *Landscape Ecology* (Fig. 10; see publications, below). Additionally, we are using data on recruitment rates at treeline from Sequoia National Park (Dr. Andrea Lloyd) and Yosemite National Park (Dr. Lisa Graumlich; and Dr. Connie Millar, USFS collaborator) to modify our forest stand simulation model to address ecotone dynamics. Also, during 1999 Ken Pierce adapted the FACET gap model to incorporate seed dispersal, using dispersal distance functions developed from Ruth Kern's seed trap data (see Clark et al. 1999, listed below). Ken used the model to explore possible feedbacks between the spatial scales of seed dispersal as compared to the scale of topographic gradients. Our hypothesis is that, if dispersal distances are short relative to topographic gradients, then seed dispersal will act as a pattern amplifier, reinforcing species distributional patterns along gradients. Ken will present preliminary results of these model experiments at the annual Landscape Ecology Symposium in Ft. Lauderdale in April 2000.

Question 4: *How does climatic change affect the spatial extent, landscape pattern, and severity of fires?*

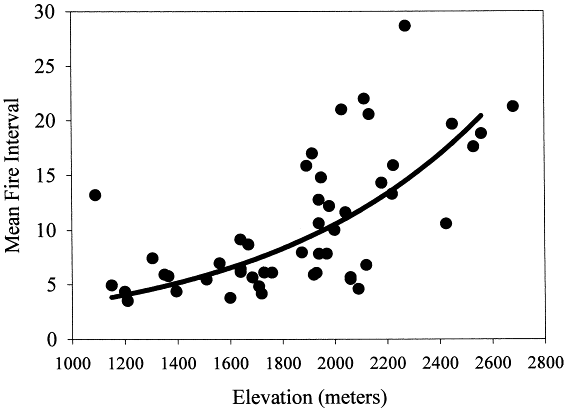

Figure 11. Mean fire intervals (at least 25% of trees scarred) pooled over all sites and plotted versus elevation. From Swetnam et al. 1998.

Analysis continued on existing fire scars within tree rings collected across four Sierra Nevada climatic (elevational) transects (Fig. 11), and within the Giant Forest sequoia grove, the site of our intensive study of spatial patterns. Data were entered into the fire history database. Fire history transects were revisited, where we developed and tested field strategy for characterization of vegetation. While most of our sampling has focussed on dead trees, a preliminary assessment was made of the impact of past fire scar sampling on live trees (usually fire-scarred pines). Some tree failures and some mortality were noted. Failures resulted from mechanical weakening of the stems. Mortality (other than failures) was most likely incidental and due to drought or other factors affecting numerous trees in the Sierra Nevada. Tree failures can be avoided in most cases by careful sampling procedures and avoiding trees with existing structural defects such as extensive heart rot. Quantification of these observations should be possible after we visit the remaining sites in the context of our stand characterization objective.

During the summer of 2000, we will address our failure to successfully date fire-scar samples in a number of north-facing and high-elevation sites will be addressed, where possible, by additional sampling. These difficulties were most pronounced in Yosemite and our efforts will be concentrated there.

Our newly-developed field strategy for characterization of vegetation will be applied in Yosemite and Sequoia-Kings Canyon. The removal of the Selective Availability from GPS signals should assist in this effort by allowing more accurate real-time application of hand-held GPS devices.

Question 5: *What are the relative importances of tree recruitment, death, and growth rates, and their interannual variabilities, in determining forest response to climatic variation in space and time?*

Our 23 long-term forest dynamics plots, established 1982 - 1994 and ranging in size from 0.9 to 2.5 ha, are arranged along a climatic (elevational) gradient from lower treeline (1500 m) to upper treeline (3100 m) (Fig. 12). All trees >1.4 m in height are tagged, mapped, and identified by species within each plot. In 1999, each of the ca. 18,000 living trees within the plots received its annual mortality check. If a tree had died, probable causes of death were determined. Tree diameter remeasurements were completed in the eight plots that were due for their 5-yr remeasurements. In the past, ingrowth (new trees reaching 1.4 m height) were only tagged and recorded every five years. In 1999 year we permanently changed our protocols to record ingrowth annually, so as to avoid the possibility of some seedlings surpassing 1.4 m height, then dying before we have a chance to record them. Stephenson completed a simple mathematical model for exploring the relative importance of growth rates and demographic rates in determining forest carbon dynamics, and exercised the model using data from the forest plots.

In Fiscal Year 2000, all plots will again be re-censused as described above. Data analysis and manuscript writing will focus on two broad topics: (1) What is the relationship between tree size, growth rates, and death rates, broken down by causes of death? (2) What are the relative importances of tree birth rates, growth rates, and death rates in determining forest carbon dynamics?

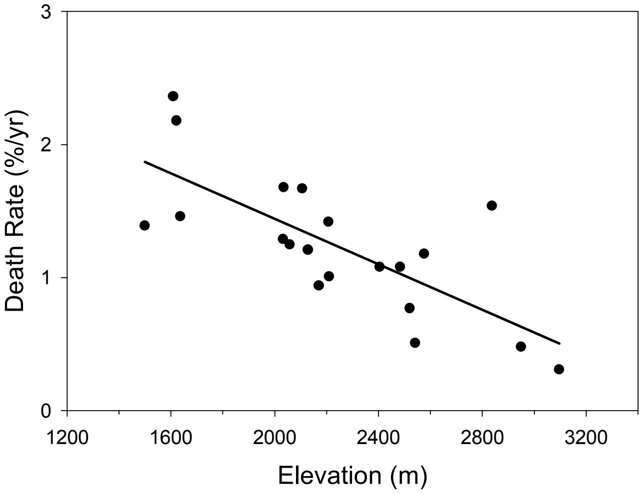

Figure 12. Tree death rates relative to elevation. From Stephenson et al. *unpublished data*.

Question 6: *What portions of Sierra Nevada landscapes are most sensitive to climatic changes (temperature, precipitation, and seasonality), what are the implications of this for a greenhouse world, and what are the implications for land managers?*

Urban submitted to *Ecological Applications* (and had accepted for publication) a manuscript using his Zelig model and its derivatives to determine which portions of the southern Sierra Nevada landscape are most sensitive to climatic change (Fig. 13), and how this knowledge can be applied by managers to design monitoring programs.

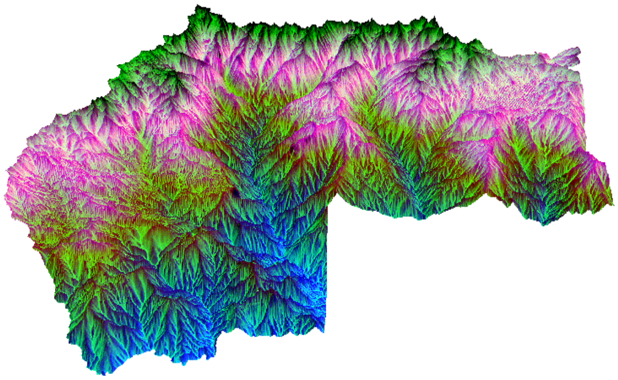

Figure 13. False-color composite image of Kaweah Basin in Sequoia National Park, illustrating relative sensitivity to climatic change. Red scales with increasing sensitivity to temperature change; blue, to change in precipitation. Green scales with increasing uncertainty due to the local influence of topographic drainage on soil moisture. Thus, magenta colors are those sites that are most sensitive to variability in temperature and precipitation. From Urban (*in press*).

Question 7: *Does climate synchronize fire regimes at subcontinental scales? If so, what large-scale climatic phenomena drive the synchrony?*

Fire-scar chronology networks were compared among the west slope of the Sierra Nevada (45 sites), the Southwestern U.S. (63 sites), the east slope of the Cascades in Washington, and the Blue Mountains in Oregon were compared (6 sites for

Washington and Oregon combined). Each of these regional networks showed a tendency for high and low fire occurrence to be synchronized during certain years. Over the period 1700 to the present, high and low fire occurrence years were compared among the regions with an independent network of drought reconstructions from tree-rings (Cook et. al. 1999, Journal of Climate, 12:1145-1162), resulting in two primary observations: (1) During particular decades, high fire occurrence years in the Southwest correspond with low fire occurrence years in Washington and Oregon, and vice versa. During other decades there are no clear patterns of synchrony or asynchrony between the Southwest and Northwest. During some years the Sierra Nevada fire regime appears to be synchronized with the Southwest, and during other years it is synchronized with the Northwest. These patterns of decadal synchrony and asynchrony are evident during the two centuries analyzed with fire scars (i.e., 1700s and 1800s), as well as in time series of area burned derived from 20th century documentary records. (2) There are strong correlations between the spatial patterns of drought over the western United States and the patterns of synchrony and asynchrony of fire years in particular regions. Overall, we expect that these spatial-temporal patterns are important clues about the changing climatic controls over fire regimes at regional to continental scales, and probably reflect very broad-scale climatic patterns and their impacts, such as the El Nino-Southern Oscillation and the Pacific Decadal Oscillation.

During fiscal year 2000, additional statistical analyses of the spatial and temporal climate and fire data will be carried out. For example, we plan to develop composite maps of the drought patterns during particular combinations of synchronous and asynchronous fire years for the different permutations of the region. We also plan to conduct various types of time series analyses in comparison of the different fire history network and drought time series.

Question 8: *Can agents of pattern formation and mechanisms of forest change be generalized at subcontinental scales?*

At the 1999 meeting of the Ecological Society of America in Spokane, Washington, Stephenson organized and facilitated a meeting of the USGS-BRD Western Mountain Initiative global change research sites (Olympic, Glacier, Colorado Rockies, and Sierra Nevada). The group re-confirmed that its domain extends to all western mountains (not just the core research areas centered on National Parks) and that it studies global changes in the broadest sense of the term, including atmospheric deposition, habitat fragmentation, land use changes, and invasive species, in addition to climatic change. Synthetic efforts of the Western Mountain Initiative will include most or all of the following: (1) analysis and interpretation of changing tree growth rates (lead: Peterson and Graumlich); (2) exotic species invasions and invasibility of ecosystems along climatic gradients (lead: Stohlgren); (3) consequences of increasing nitrogen deposition (lead: Baron); (4) climate-fire relations at a subcontinental scale (lead: Swetnam and Veblen); (5) changing forest dynamics along climatic gradients (lead: Stephenson); (6) vulnerability assessments (identify site sensitivities) (lead: Urban); and (7) integrate and interpret palynological data at a regional scale.

In Fiscal Year 2000, the Western Mountain Initiative (WMI) will present preliminary syntheses on several of these topics at a WMI-organized symposium (“Stressors in Western Mountain Ecosystems: Detecting Change and its Consequences”) at the annual meeting of the Ecological Society of America. The Sierra Nevada Global Change Research Program will contribute heavily to three of the seven symposium talks: “1000 years of climate change and ecological response in western montane forests” (Graumlich); “Altered disturbance regimes: fire, fuels, and forest structure" (Stephenson, Swetnam, and Veblen); "Exotic species and biodiversity in mountain forests" (Stohlgren, Keeley, and Graber).

Question 9: *How do the relative importances of agents of pattern formation vary among different climates? Is our understanding of mechanisms of forest change sufficient for a single model to explain forest dynamics at several different sites across the continent?*

This ambitious and seminal effort is the brainchild of Dr. Dean Urban (Duke University), and has been supported largely by his NSF Terrestrial Ecosystems [TECO] grant IBN #96-52656, with heavy local collaboration and integration with the Sierra Nevada Global Change Research Program. The TECO project is a model-based comparison of montane forest systems in the Oregon Cascades (H. J. Andrews Forest), the White Mountains of New Hampshire (Hubbard Brook Experimental Forest), and the southern Appalachians in western North Carolina (Coweeta Hydrologic Lab).

In Fiscal Year 2000, Urban will apply to NSF/LTER for a continuation of funds in support of this cross-site comparison effort. Urban will use summer 2000 to conduct a pilot study of two new sampling methods developed as part of this new proposal.

PARTNERSHIPS AND COLLABORATION

Beyond our integral and indispensable collaboration with our principal investigators at Duke University (Dr. Dean Urban), Montana State University (Dr. Lisa Graumlich), and the University of Arizona (Dr. Tom Swetnam), the Sierra Nevada Global Change Research Program includes the following partnerships and collaborations.

University of Washington and Oregon State University

A productive collaboration was established with Dr. Jerry Franklin, University or Washington, and Dr. Steve Acker, Oregon State University. Franklin and Acker have generously supplied forest demographic data similar to those collected by the Sierra Nevada Global Change Research Program, but from Mount Rainier, Washington. The Rainier data will provide a valuable contrast to the Sierra Nevada data, allowing us to look for broad generalities about relationships between climate and forest dynamics. Franklin and Acker are working with the Sierra Nevada principal investigators in writing a manuscript presenting preliminary results.

University of California

Collaboration continued with Kurt Menning, doctoral candidate, and Dr. John Battles, assistant professor at U.C. Berkeley. Stephenson serves on Menning's doctoral committee, which is chaired by Battles. Menning's dissertation focusses on changes in forest pattern at landscape scales, particularly as influenced by the reintroduction of fire after a long period of exclusion (Fig. 14). His approach is to analyze remote imagery before and after prescribed fires in Sierra Nevada mixed-conifer forest, and link changes that are evident in the imagery to changes recorded in two hundred ground-truth plots. Battles is investigating causes of a severe die-off in sugar pine (*Pinus lambertiana*) that is occurring in both burned and unburned stands.

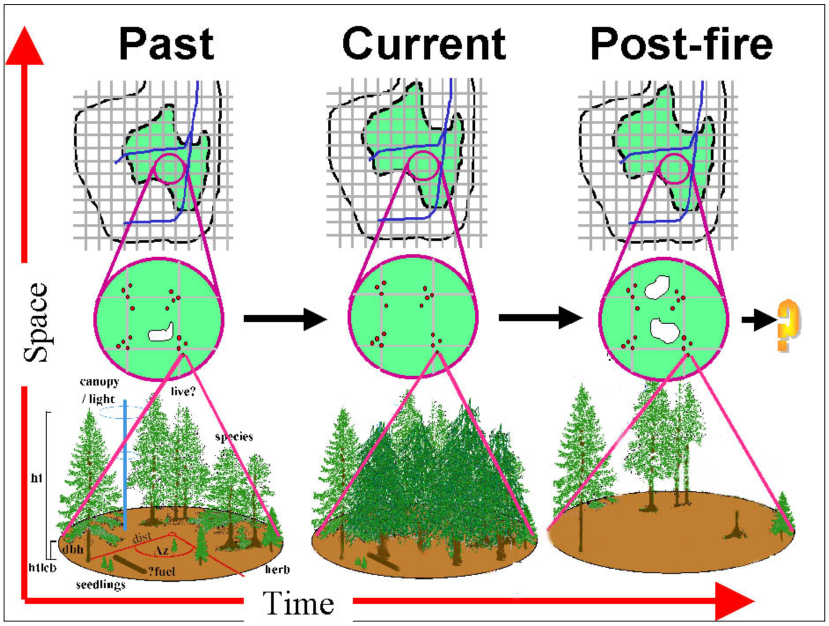

Figure 14. Potential Sierra Nevada forest structure with and without the application of fire. From Menning (*unpublished*).

Department of Interior/U.S. Forest Service, Joint Fire Science Program

Keeley and Stephenson have been key players in developing a proposal for a national program to determine the ecological consequences of different approaches to forest fuels management (*http://ffs.psw.fs.fed.us/*). The five-year, multi-site, multi-million dollar proposal has been funded through the Department of Interior/U.S. Forest Service Joint Fire Science Program (*http://www.nifc.gov/joint_fire_sci/index.html/*). In the southern Sierra Nevada, research will begin in fiscal year 2001, and will focus on determining the ecological consequences of different seasons of prescribed fires. The study will benefit from previous findings of the Sierra Nevada Global Change Research Program, and in turn will nicely complement that program by enhancing our understanding of the role of fire in forest dynamics, particularly regeneration.

U.S. Forest Service

The Sierra Nevada Global Change Research Program welcomed the addition of Dr. Connie Millar, U.S. Forest Service, Pacific Southwest Forest and Range Experiment Station, as a formal collaborator. Dr. Millar has extensive experience in the genetics, history, and paleoecology of Sierra Nevada forests, with several study sites on National Forest land adjacent to the Program's primary study sites in the national parks. While Dr. Millar initially will be collaborating most extensively with Dr. Graumlich on studies of Sierra Nevada treeline dynamics, further collaborations on dynamics of lower-elevation forests are under discussion.

National Interagency Fire Center

Keeley and Stephenson secured funding from the National Interagency Fire Center (Boise, Idaho) to determine changes in Sierra Nevada forest structure since the late 1800s through repeat photography (Fig. 15). This study will supply land managers in the Sierra Nevada with information needed to set structural goals for forest restoration, and will supply the Sierra Nevada Global Change Research Program will valuable information on the relationships between changing climate, fire regimes, and forest structure. This study will differ from past repeat-photography studies in that it will (1) attempt to provide an unbiased view of forest changes, rather than selecting the photo pairs that demonstrate the most dramatic changes; (2) attempt to quantify changes in surface fuels and tree sizes and densities, rather than presenting qualitative results; and (3) focus some efforts on the lower forest-shrubland ecotone, which appears to have shifted over the last century but has generally not been studied.

U.S. Geological Survey's Western Mountain Initiative

As described earlier in this report, the global change research programs of the USGS-BRD Western Mountain Initiative (WMI) -- Olympic, Glacier, Colorado Rockies, and Sierra Nevada -- are collaborating to draw generalizations that extend beyond their individual sites (Fig. 16). In Fiscal Year 2000, the WMI will present preliminary syntheses on several topics at a WMI-organized symposium ("Stressors in Western Mountain Ecosystems: Detecting Change and its Consequences") at the annual meeting of the Ecological Society of America. The Sierra Nevada Global Change Research Program will contribute heavily to three of the seven symposium talks: "1000 years of climate change and ecological response in western montane forests" (Graumlich); "Altered disturbance regimes: fire, fuels, and forest structure" (Stephenson, Swetnam, and Veblen); "Exotic species and biodiversity in mountain forests" (Stohlgren, Keeley, and Graber).

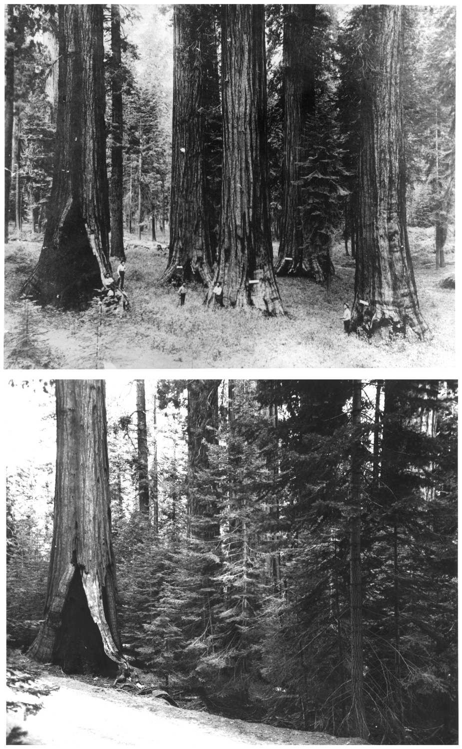

Figure 15. Comparisons of historic (top) to current (bottom) photographs show dramatic changes in forest structure in the Sierra Nevada. From Stephenson 1999.

Yosemite and Sequoia and Kings Canyon national parks

The global change staff continued its close working relationship with personnel in the Division of Science and Natural Resources Management at Sequoia and Kings Canyon National Parks. Both groups share many common goals and data sets. Interactions include mutual assistance in experimental and monitoring design, mutual field assistance, assistance in data analysis, exchanges of related data sets, and exchange of relevant research findings.

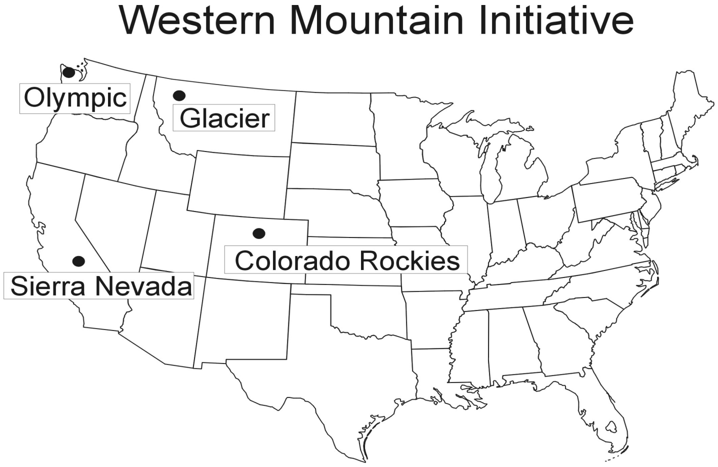

Figure 16. The Western Mountain Initiative sites.

1999 OUTREACH AND TECHNICAL ASSISTANCE

News Media

Stephenson was interviewed by both USA Today and the Sacramento Bee on giant sequoia ecology and management. The interviews focussed heavily on knowledge gained from the Sierra Nevada Global Change Research Program, including fire history and the effects of climatic change on giant sequoia populations. Both stories ran on the newspapers' front pages. Stephenson was also interviewed by a Japanese film crew for a documentary on fire and forest management, and supplied information on giant sequoias to ABC News to be used in its television special celebrating the millennium. Keeley was interviewed by the producer of Nova for an upcoming documentary on fire.

Universities and schools

Keeley and Stephenson were invited participants at a workshop convened by planners of the newest University of California campus, U.C. Merced. The workshop focussed on setting priorities for the University's research focus the Sierra Nevada (including global change), and possible future collaborations. Stephenson gave a presentation to a visiting French school group, focussing on giant sequoia ecology and findings of the Sierra Nevada Global Change Research Program. Keeley gave invited presentations on his fire ecology research at the University of Montana and the University of Calgary.

NGOs and the private sector

Stephenson was called upon by the Save-the-Redwoods League to help assess the privately-held Dillonwood grove of giant sequoias for possible purchase and donation to the National Park Service. Keeley was the invited after-dinner speaker at a meeting of the Society of American Foresters, Sacramento Chapter.

Federal, state, and local agencies

Stephenson remained an active participant of the interagency Giant Sequoia Ecology Cooperative, which includes representatives from the U.S. Forest Service, National Park Service, Bureau of Land Management, California Department of Forestry and Fire Protection, California Department of Parks and Recreation, University of California, and U.S. Geological Survey. The Cooperative provides a forum for exchanging research findings and implications related to the management of giant sequoia ecosystems. Additionally, Stephenson was an invited speaker at the U.S. Forest Service workshop in Sacramento on "Giant Sequoias: a Blueprint for Change." Keeley was an invited speaker at a symposium sponsored by USDA and USGS on biodiversity and fire. Keeley also participated in a fire modeling workshop funded by the Joint Fire Science Board and held at the Angeles National Forest.

Department of Interior

Stephenson acted as a subject matter expert during a fact-finding field trip by Tim Ahern, Secretary of Interior Bruce Babbitt's press secretary, in Sequoia and King's Canyon National Parks. Keeley contributed a peer review to the U.S. Fish and Wildlife Service on their "Draft Recovery Plan for Gabbro Soil Plants of the Central Sierra Nevada Foothills." Keeley also participated in a Bureau of Land Management (BLM) field trip to observe and discuss management of Case Mountain, BLM (Tulare County).

National Park Service

Stephenson, van Wagtendonk, and Keeley were invited speakers and participants at an interagency workshop in Rancho Cordova, convened by the National Park Service, aimed at defining forest structural goals for prescribed fire programs in the Sierra Nevada and southern Cascades. The workshop drew on their knowledge of past forest conditions, in a large part derived from findings of the Sierra Nevada Global Change Research Program. In a similar capacity, Keeley consulted on fire management objectives with the fire management team at Redwoods National Park. Keeley also participated in a workshop to define fire objectives for southern California national parks and monuments, and contributed to another workshop to develop inventory and monitoring strategies for these parks.

Yosemite and Sequoia and Kings Canyon national parks

Through technical assistance, members of the Sierra Nevada Global Change Research Program played integral roles in the management of the national parks of the Sierra Nevada. In Sequoia and Kings Canyon National Parks, Stephenson and Keeley provided extensive and detailed scientific input into the Parks' revision of its Natural Resources Management Plan and Fire Management Plan. Stephenson and Keeley also served as members of the Parks' Fire Management Committee, helping with management decision-making and supplying information needed for setting fire management goals. Both scientists also acted as consultants in planning the Parks' multi-year, multi-million dollar vegetation mapping initiative. Stephenson assisted with annual training of the Parks' interpretive staff, updating them on the latest findings of the Sierra Nevada Global Change Research Program. Additionally, Stephenson acted as a consultant on the construction of a new, multi-million dollar Park museum, supplying relevant scientific information and fact-checking text for the proposed displays. Global Change staff members responded to many other requests for assistance by supplying the Parks with, for example, information on an outbreak of the defoliating Douglas-fir tussock moth (data gleaned from our long-term forest monitoring plots), and meteorological data needed by the Parks' maintenance staff for construction design.

Stephenson, Keeley, and van Wagtendonk gave formal presentations and participated in a major workshop aimed at designing a comprehensive ecosystem monitoring program for the national parks of the Sierra Nevada.

PROGRESS TOWARD A SYNTHETIC BOOK

Fiscal Year 2000 will see a major push to integrate and synthesize results to date of the Sierra Nevada Global Change Research Program. The principal investigators and other potential chapter authors will meet in the Sierra Nevada in spring 2000 to compile chapter outlines. Our tentative book outline is as follows:

1. Introduction: Overarching themes

THE PHYSICAL TEMPLATE

2. Contemporary climate and water balance
3. Late Holocene climatic variation
4. Scaling the physical drivers of forest pattern

DISTURBANCE

5. Contemporary fire behavior and effects
6. Late Holocene fire regimes
7. Scaling fire regimes in space

BIOTIC PROCESSES

8. Recruitment
9. Growth
10. Mortality

INTEGRATION

11. Interactions, feedbacks, and couplings
12. Scales of variability and the pattern, pace, and mechanisms of change
13. Synthesis and prospectus

1999 PUBLICATIONS AND PRESENTATIONS

Publications

A complete bibliography of the Sierra Nevada Global Change Research Program since its inception can be found at *http://www.werc.usgs.gov/sngc/*. The following publications were accepted for publication or published during calendar year 1999 only.

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