Global Change in Wilderness Areas: Disentangling Natural and Anthropogenic Changes

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Abstract—Human impacts on the Earth's ecosystems are globally pervasive. Wilderness areas, although largely protected from direct human impact at local scales, nevertheless are subject to global changes in atmospheric composition, climate and biodiversity. Research in wilderness areas plays a critical role in disentangling natural and anthropogenic changes in ecosystems by providing a network of sites where local impacts are minimized relative to adjacent, more intensely managed areas. Three case studies are discussed to illustrate the role of wilderness areas in global change research and, specifically, how paleoecological data provide baseline documentation of variability in climate and ecosystem processes.

The motivation to designate wilderness areas as research sites stems from a recognition that human influences on the Earth's ecosystems are multiple and pervasive. As such, wilderness areas, and more generally biosphere reserves, are traditionally thought of as parcels of land protected from human influence. A theme that strongly emerges from contributions to the Wilderness Science in a Time of Change Conference is that wilderness boundaries are porous with respect to human impacts, especially those impacts commonly referred to as global change. In this paper, I explore opportunities for research in wilderness areas engendered by increasingly complex relationships between human agency and the environment.

In considering the current and potential impacts of global change on wilderness areas, it is useful to define global change broadly enough to encompass both systemic and cumulative changes (Turner and others 1990; fig. 1). Systemic impacts on the Earth, such as increasing trace gases, are global because the atmosphere dynamically mixes carbon dioxide and other gases, and their impacts on ecosystems and the climate system are registered over the entire Earth. Cumulative impacts on the Earth, such as land-use change, changes in biodiversity and alteration of the nitrogen cycle, are increasingly global in scale due to the accretion of local and regional changes (Vitousek and others 1997; Vitousek this volume). Under this perspective of global change, wilderness boundaries offer little or no protection from either systemic global changes, such as increasing carbon dioxide and associated changes in climate, or cumulative global changes, such as changes in fire regime or invasive species.

Given that human impacts on ecosystems increasingly extend to areas previously considered pristine, what role can wilderness, or more generally protected areas, play in scientific research? The answer lies in two veins of inquiry that have become increasingly important in the attempt to disentangle natural and anthropogenic environmental changes. First, research based in wilderness and other less managed areas is critical to detecting the impact of climate change because it uses settings with minimal human influence. In essence, protected areas can be thought of as the "canaries in the coal mine," that is, sites where impacts may initially be manifest. Second, research in protected areas offers a powerful approach to the problem of attributing change to human vs. natural causes. Protected areas, in combination with adjacent, more intensely managed areas, offer settings where human alteration of ecosystems processes can be observed and, in many cases, quantified (Vitousek this volume). In this context, paleoecologists have vigorously exploited wilderness areas as sites for research aimed at detecting global changes as well as attributing changes to appropriate drivers. As such, wilderness areas are rich repositories of paleoclimate and paleoecological data (for example, tree rings, sediment cores, macrofossil deposits). The significance of these natural archives is that they allow us to study climate-ecosystem interactions under conditions that are novel compared to present conditions.

In this paper, I argue for the value of wilderness areas as sites for research by reviewing three case studies in which

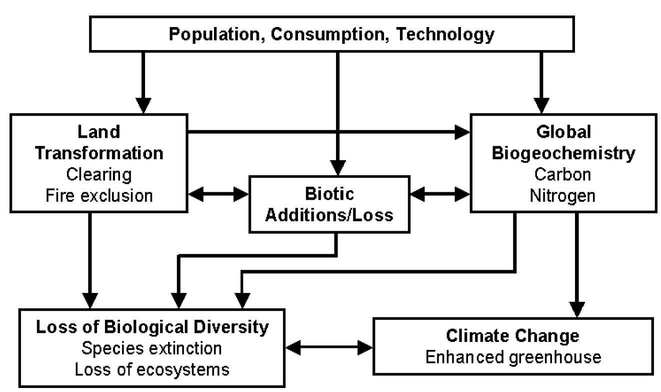

Figure 1—A conceptual model illustrating humanity's direct and indirect effects on the Earth system (modified from Vitousek and others 1997).

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paleoenvironmental data from large natural areas enhanced our understanding of the current and potential impact of global environmental change on climate—ecosystem interactions. The case studies were chosen, in part, for their ability to describe dynamics over the past 1,000+ years. The last millennium encompasses variability in climate exceeding that observed during the 20th century (Graumlich 1993; Hughes and Diaz 1994). Well-documented anomalies in past climate present us with an opportunity to study climate—ecosystem interactions falling outside the bounds of multi-year field observations, or even historical records spanning the current century (Graumlich and Brubaker 1995). Finally, the case studies were chosen to illustrate the range of scales at which paleoenvironmental data can contribute to our understanding of natural variability and process. The case studies and associated scales of research are:

- A landscape-scale study of upper treeline in the southern Sierra Nevada that documents dramatic ecotonal changes over 3,000+ years (Lloyd and Graumlich 1997)
- A regionally scaled study of climate, fire and forest interactions in the American Southwest (Swetnam and Betancourt 1998)
- A globally scaled study of the nature of climate variability and its causes (Mann and others 1998; Mann and others 1999)

Landscape-Scale Research: Multi-millennial Records of Climate Variation and Treeline Response in the Sierra Nevada

Paleoecological records from protected areas have been critical to development of our current understanding of how climatic variability affects forests, especially forests growing at or near their temperature limits. In particular, studies of alpine treeline have indicated that it is a sensitive ecotone, responding to multi-decadal temperature trends (Graumlich 1994; Körner 1998). As such, when seedlings established above current treeline during the past several decades at mid- and high latitude sites, some interpreted it as an indicator of global warming (Rochefort and others 1994). If we are to use upper treeline as a bellwether of global climate change, we must understand the processes that control its variability. Defining the variability of relevant population processes requires observations that span several decades, if not centuries, as a baseline.

Dendroecological studies of treeline have provided context for assessing current observations of directional change at this ecotone. The case study below describes work I did with Andrea Lloyd in the southern Sierra Nevada, where we have taken advantage of relatively pristine study sites to examine population processes influenced by multi-decadal changes in climate (Lloyd and Graumlich 1997). In particular, we investigated two questions: 1) How has the abundance of trees beyond the current distributional limits of subalpine forests changed over the past few millennia? 2) How do changes in the position and population structure of subalpine forests relate to climate variability?

Dead trees at and above treeline in the eastern Sierra Nevada of California are preserved in situ for millennia. Such subfossil wood testifies to the dynamic behavior of treeline in the late Holocene. Recent seedling establishment above current treeline suggests that forest structure and composition changes may be accelerating and continue in the future. The combination of recent ecotone change and highly resolved paleoecological records presented an opportunity to place vegetation dynamics of the past decade into a broader context to determine if current dynamics had analogs in the past and, if so, to attribute past changes to appropriate driving factors. More specifically, we combined investigations of climatic history from tree rings and other proxy climatic sources with studies of foxtail pine (*Pinus balfouriana*) treeline dynamics on the eastern crest of the Sierra Nevada in Sequoia and Kings Canyon National Parks.

The climate history of the Sierra Nevada biogeographic region is well known from a wealth of independent paleoclimatic data. Tree-ring data from subalpine conifers and giant sequoia (*Sequoia semprevirens*) in the Sierra Nevada and bristlecone pine (*Pinus longaeva*) in the adjacent White Mountains provide well-validated inferences about seasonal climatic variation (Graumlich 1993; Hughes and Brown 1992; Hughes and Graumlich 1996). The summer temperature reconstruction shows fluctuations on centennial and longer time scales, including a period with temperatures exceeding late 20th century values from ca. AD 1100 to 1375, corresponding to the Medieval Warm Period identified in other proxy data sources, and a period of cold temperatures from ca. 1450 to 1850, corresponding to the documented Little Ice Age. Reconstructed precipitation variation is dominated by shorter period, decadal-scale oscillations punctuated by very severe single-year drought approximately two to three times per century. A surprising feature of the records is the documentation of multi-decadal droughts (AD 1050-1100 and AD 1200-1350) of much greater severity and length than the drought experienced by California from 1928-1934. These droughts are corroborated by evidence from Mono Lake, located on the east side of the Sierra Nevada (Stine 1994). Tree stump remains were found in place when levels of Mono Lake were artificially lowered over the past several decades. The stumps offer firm evidence that water supplies originating in the Sierra Nevada were reduced to 40% of the 20th century average during long periods in the past.

Treeline dynamics for the past 3,500 years were reconstructed from a tree-ring analysis of subfossil wood at and above current treeline (Lloyd and Graumlich 1997). Treeline elevation in the foxtail pine forests is between 3,300 and 3,500 m in a climate currently characterized as both cold and dry. Because foxtail pine does not adopt a krummholz growth form characteristic of many treeline species, treeline is a relatively abrupt boundary (fig. 2). We selected five study sites at which to reconstruct past changes in tree abundance and treeline position: three sites adjacent to and above current treeline and two sites where changes in treeline were expressed along gradients related to aspect. At each 1-4 ha site, we cored and mapped all subfossil wood. The vast majority of the dead wood could be dated such that we could determine a date of establishment of the adult tree (pith date) and the death date of the tree (outer ring data with correction for sapwood loss).

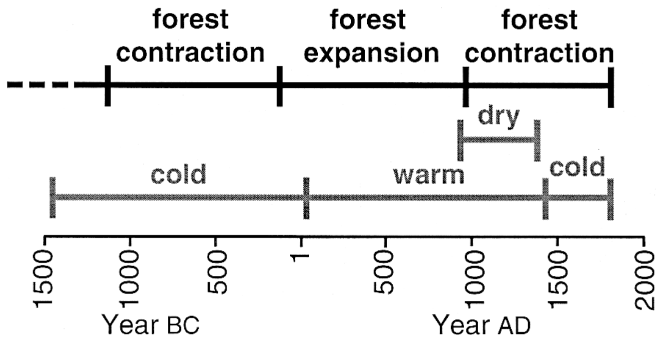

Figure 2—History of abundance of foxtail pine populations at treeline in the eastern Sierra Nevada of California in comparison to past climatic variation over the past 3,500 years. Treeline data are from dates of recruitment and mortality of adult trees at five sites in the region (Lloyd and Graumlich 1997). Climate inferences are from tree ring and geomorphic records (Graumlich 1993; Hughes and Graumlich 1996; Stine 1994).

Our results show that the abundance of trees above treeline changed over the past several millennia in concert with changes in climate (fig. 2). A relatively dense forest grew above current treeline from the beginning of our records to around 100 BC and again from AD 400 to 1000, when temperatures were warm. Abundance of trees and elevation of treeline declined very rapidly from AD 1000 to 1400, the period of severe, multi-decadal droughts. Treeline declined more slowly from AD 1500 to 1900 under the cool temperatures of the Little Ice Age, reaching current elevations around AD 1900. These results indicate that while temperature is an important control on treeline dynamics, the influence of temperature can be modified by drought. In fact, drought can reverse the expected relationship between warm temperatures and increasing populations at treeline, as seen in the period AD 1000 to 1400.

The record of foxtail pine treeline dynamics speaks to the question of whether we are currently witnessing human impacts on climate—vegetation systems. Results from other paleoclimatic studies are similar, indicating a high degree of climatic variability in the past, especially at multi-decadal to multi-century time scales. The treeline results, while only for a single locality, strongly indicate that treeline response to 20th century warming, in the form of seedling establishment above treeline, does not yet exceed changes observed in the past 1,000 years. Thus, the movement of this ecotone does not, at this point, offer evidence of unprecedented change that can be attributed to human activity.

Regional-Scale Research: Climate, Fire, and Forests in the American Southwest

Most studies of disturbance—ecosystem interactions have emphasized local processes and short-time scales. Such research typically focuses on the role of disturbance in creating heterogeneity, specifically patches of different age and/or composition within a landscape. A recent compilation and synthesis of a decade of research on fire ecology in the American Southwest by Swetnam and Betancourt (1998) offers an important counter to previous studies of disturbance by demonstrating how climate synchronizes fires at regional scales. Regionally scaled fires reset demographic clocks over wide areas, thereby creating similarities in age structures between fire-prone landscapes within a region. The work of Swetnam and Betancourt thus makes an ideal case study demonstrating that research conducted at multiple wilderness sites brings new understanding. In describing their results, I emphasize two innovations in their work. First, an accurate and precise chronology of disturbance events could be documented because low-intensity fires in the Southwest leave a legacy in the form of fire scars that can be dated to the calendar year. Second, a regional approach to the question of climate-fire relationships was feasible because of the existence of a network of wilderness areas and other reserves managed by federal and state agencies that requested and, in many cases, supported the reconstruction of fire history.

Dating of wildfire events that occurred during the past several hundred to several thousand years is possible because low-intensity surface fires are sufficiently hot to damage to the cambium and outermost xylem cells of a tree but not to kill the tree. The resulting fire scars, when magnified in cross-section, show a heat-caused lesion in the xylem tissue. Using techniques of dendrochronology, the scar can be assigned to an exact calendar year and, in many cases, can be linked to a specific season of the year (Fritts and Swetnam 1989). When multiple synchronous fire scar dates are established for numbers of trees at a site, the resulting fire scar chronology is interpreted as a record of wildfires at that site. Such fire scar chronologies have been important in providing guidance to land managers for the frequency and scale at which to reintroduce fire into areas where fire exclusion during the 20th century produced undesired changes in forest structure or composition (for example, Swetnam 1993).

Because the fire scar chronologies for each site are absolutely dated, they can be aggregated to form a regional composite chronology. The most comprehensive composite fire-scar record to date is for the American Southwest and consists of 63 separate fire scar chronologies from 25 different mountain ranges (Swetnam and Betancourt 1998). Each fire-scar chronology within the composite is based on 10 or more trees per stand where stands ranged in size from 10 to 100 ha within ponderosa pine (*Pinus ponderosa*) or mixed conifer woodlands.

The composite fire scar record for the American Southwest indicates that regionally synchronous fires recurred regularly during the period 1700 to 1900 (fig. 3; Swetnam and Betancourt 1998). At individual sites, fires occurred approximately every 7.5 years. At this rate, regionally synchronous fires (defined as fires occurring in one-third of all sites in a given year) would occur by chance alone once every 35,000 years. Instead, the composite record shows regionally synchronous fires occurred 15 times in the 201-year period. Of particular note is the record for 1748, when 41 out of 63 sites experienced a fire. The probability of the 1748 event occurring by chance is one in billions. Swetnam and Betancourt argue that the synchronization of fires at the regional scale must reflect regional to subcontinental drought for one or more seasons. To support this claim, they note the strong correlation between an independent record of Palmer

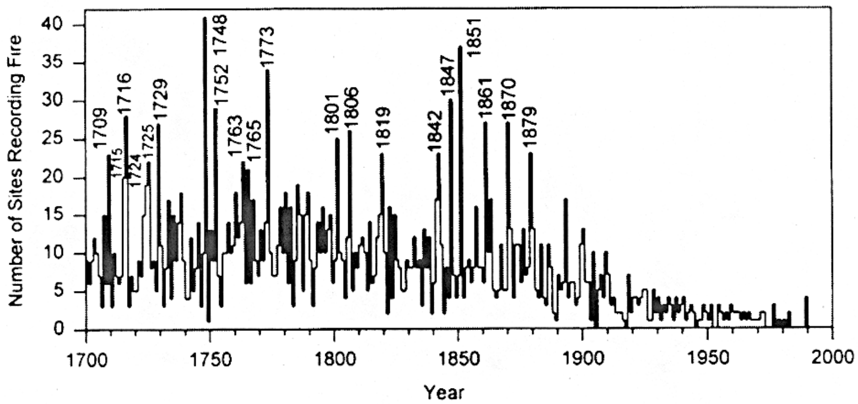

Figure 3—History of fires affecting large portions of the ponderosa pine and mixed conifer forests of the American Southwest as inferred from a network of fire scar records (modified from Swetnam and Betancourt 1998). Years marked with calendar date represent events in which at least one third of sites recorded a fire.

Drought Severity Index (PDSI) and the number of large fires (fig. 4). Drought and fire are, in turn, strongly associated with decadal-scale shifts in the El Niño—Southern Oscillation (ENSO). In particular, high amplitude and rapid shifts between ENSO modes (1740-1780; 1830-1860) are associated with shifts from extreme wet to extreme dry years. The combination of wet anomalies, which induce higher than normal fine-fuel production, followed by dry anomalies is the most important factor for entraining fire occurrence across the region.

The results of Swetnam and Betancourt underscore the importance of assessing ecological patterns and processes at appropriate scales. Their discovery of the role of climatic variation, especially ENSO fluctuations, in synchronizing wildfire across the American Southwest was based on a data set of sufficient size and length of record to uncover the phenomena. Their results give added meaning to the characterization of ecosystems as historically contingent systems, whose structure and dynamics reflect the legacy of the past.

Global-Scale Research: A 1,000-Year Record of Northern Hemisphere Temperature Sheds Light on Recent Anthropogenic Impacts

Arguably, one of the most important scientific questions of the turn of the millennium is deceptively simple: Has human activity changed the Earth's climate? Detecting the impact of increased greenhouse gases on the climate system has remained a vexing problem for the scientific community because the climate system varies naturally on time scales of seasons to millennia. Hence, the challenge in detecting human impact lies in disentangling the effects of increasing greenhouse gases during the 20th century from other factors that cause long-term trends in global climate (such as, variation in solar output and volcanic dust injected into the atmosphere). Instrumental weather data, which extend back approximately 100 years in most parts of the world, are

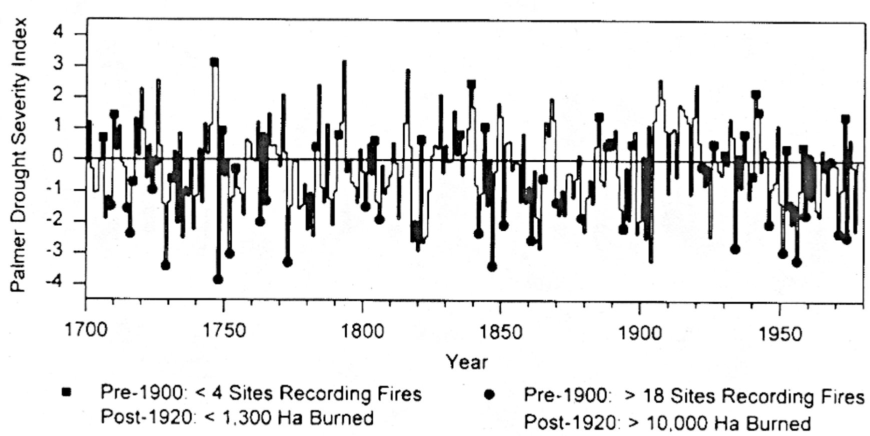

Figure 4—Severe droughts, as reflected in low values of the Palmer Drought Severity Index, synchronize fires in the American Southwest (modified from Swetnam and Betancourt 1998). Conversely, wet years are characterized by a small number of fires with minimal area affected.

inadequate to account for the nature and impact of these other climate change factors. Without temperature records that extend back hundred of years, we cannot determine whether the record high temperatures observed during the 1990s represent greenhouse gas effects or are simply an expression of natural climatic variability.

Mann and others (1998, 1999) recently published a 1,000-year long record of Northern Hemisphere temperature that provides the first strong evidence that 20th century temperature trends in the northern hemisphere exceed those that would be expected from natural variability alone. These new results represent a synthesis of a global network of hundreds of proxy climate records derived from tree rings, glacial ice and lake and ocean sediments, the vast majority of which were collected in wilderness and other protected areas where such climatic proxy data are preserved. Mann and collaborators validated their temperature inferences by demonstrating that the proxy temperature observations are strongly correlated with observational data during the 20th century.

Prior to the 20th century, the 1,000-year record shows slow oscillations of warm and cool temperatures superimposed on a 900-year cooling trend of approximately 1°C (Fig. 5). Comparison of these oscillations with patterns of solar variability and volcanic dust in the atmosphere strongly indicates that these two factors combined to produce the long-term cooling trend, as well as the shorter-term fluctuations in temperature before 1900. The 20th century, in contrast, is dominated by an abrupt increase of approximately 0.5°C. The remarkable nature of recent temperature trends in clear: The decade of the 1990s is the warmest of the last millennium and 1998 is the warmest year observed in the full 1000-year record. The 20th century temperature trend mirrors the rate of accumulation of greenhouse gases. There is no correspondence between the 20th century temperature trends and other possible natural forcing factors such as solar variability. In sum, the 1,000-year Northern Hemisphere temperature reconstruction is the first strong indication that we are now entering a period of Earth's history when human imprint on climate can be detected. This finding adds urgency to the call for including potential climate change scenarios into planning for the management of wilderness areas.

Conclusions

The studies discussed above echo common themes concerning the modern role of wilderness and other protected areas as sites of scientific inquiry. In all cases, opportunities created by the presence of natural areas amid more heavily managed lands allow us to more fully characterize the imprint of human activity on natural ecosystems. Further, when we exploit paleoenvironmental archives derived from these study sites, we define the background variability of the processes that shape ecosystems. Understanding the nature of this variability, both in terms of its causes and its consequences, is increasingly recognized as a key to sound ecosystem management (Morgan and others 1994). Finally, we are increasingly challenged to understand the relationship between changes observed on a given landscape in the context of regional and global trajectories. This task requires the continued development of networks of wilderness and large natural areas to facilitate cross-site comparisons and cross-scale analyses necessary to elucidate the complex interactions between global changes and local response.

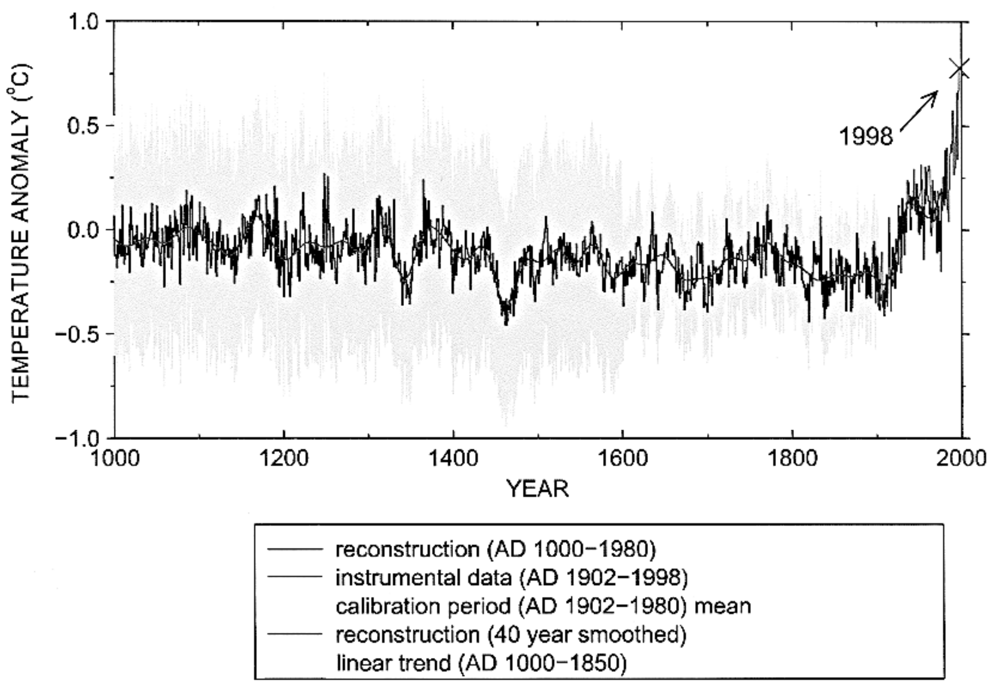

Figure 5—A 1,000-year record of Northern Hemisphere annual temperature inferred from tree rings, glacial ice, corals, and historical records (modified from Mann and others 1999).

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References

Fritts, H. C. and Swetnam, T. W. 1989. Dendroecology: a tool for evaluating variations in past and present forest environments. Advances in Ecological Research 19:111-188

Graumlich, L.J. 1993. A 1000-year record of temperature and precipitation in the Sierra Nevada. Quaternary Research 39, 249-255.

Graumlich, L.J. 1994. Long-term vegetation change in mountain environments: Paleoecological insights into modern vegetation dynamics. In *Mountain Environments in Changing Climates*, M. Beniston, ed., Routledge, London, pp. 167-179.

Graumlich, L.J. and L.B. Brubaker. 1995. Long-term records of growth and distribution of conifers: Integration of Paleoecology and Physiological Ecology. In *Ecophysiology of Coniferous Forests*, W.K. Smith and T.M. Hinckley, eds., Academic Press, New York, pp. 37-62.

Hughes, M. K. and Diaz, H, F. 1994. The Medieval Warm Period. Dordrecht: Kluwer Academic Publishers. 342 p.

Hughes, M.K. and L.J. Graumlich. 1996. Multimillennial dendroclimatic records from the western United States. In Climatic Variations and Forcing Mechanisms of the last 2000 Years, R.S. Bradley, P.D. Jones, and J. Jouzel. NATO Advanced Studies Workshop Series. Springer-Verlag.

Hughes, M.K. and P.M. Brown. 1992. Drought frequency in central California since 101 BC recorded in giant sequoia tree rings. Climate Dynamics 6, 161-167.

Körner, Ch. 1998. A reassessment of high elevation treeline positions and their explations. Oecologia 115: 445-459.

Lloyd, A.H. and L.J. Graumlich. 1997. Holocene dynamics of treeline forests in the Sierra Nevada. *Ecology* 78, 1199-1210.

Mann, M.. E., Bradley, R. S., and M. K. Hughes. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392: 779-787.

Mann, M. E., Bradley, R. S., and M. K. Hughes. 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. Geophysical Research Letters 26: 759-762.

Morgan, P., Aplet, G. H., Haufer, J. B., Humphries, H. C., Moore, M. M., and Wilson, W. D. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry 2:87-111.

Rochefort, R. M., Little, R. L., Woodward, A., Peterson, D.L. 1994. Changes in sub-alpine tree distribution in western North America: a review of climatic and other causal factors. Holocene 4, 89-100.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. Nature 369: 546-549.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. Science 262:885-889.

Swetnam, T.W. and J.L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate 11,3128-3147.

Turner II, B. L., Kasperson, R. E., Meyer, W. B., Dow, K., Golding, D., Kasperson, J. X., Mitchell, R. C., and Ratick, S. J. 1990. Two types of global environmental change: definitional and spatial-scale issues in their human dimensions. Global Environmental Change: Human and Policy Dimensions 1 (1): 14-22.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M. 1997. Human domination of earth's ecosystems. Science 277 (5325): 494 - 499.