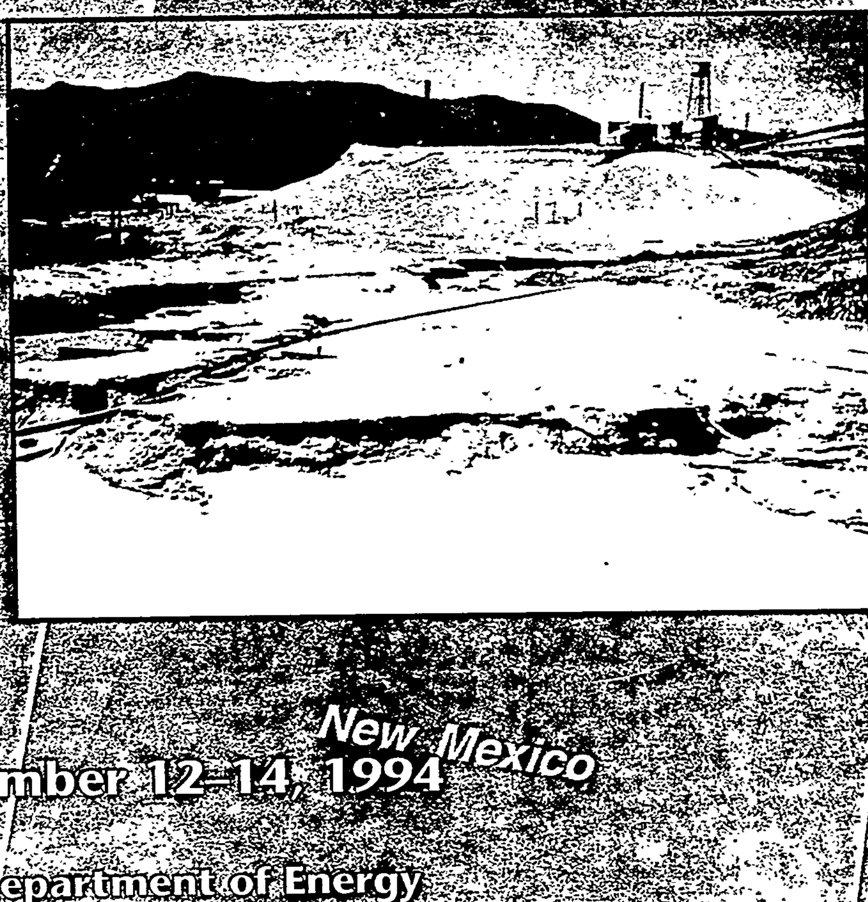
Workshop Proceedings

Climate Change in the Four Corners and Adjacent Regions

Implications for Environmental Restoration and Land-Use Planning



New Mexico

September 12–14, 1994

U.S. Department of Energy
Grand Junction Projects Office
Grand Junction, Colorado

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Proceedings of the Workshop

Climate Change in the Four Corners and Adjacent Regions: Implications for Environmental Restoration and Land-Use Planning

September 12–14, 1994

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Campbell College Center
Mesa State College
Grand Junction, Colorado

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PREFACE

Public awareness of human influences on environmental processes that sustain life is on the rise. As public trustees, environmental scientists and land managers are seeking a clearer understanding of how best to keep the biosphere in good repair. We acknowledge that some of our techniques have been short sighted, flawed, and even counterproductive. As a result, many of us are committed to developing better tools. In general, we are committed to conforming our practices with natural processes rather than attempting to conquer nature. This publication, which reflects that commitment, consists of papers presented at an interagency, interdisciplinary workshop that focused on applications of information about changes in past environments. With the possible exception of humans, climate is the principal driver of long-term environmental change.

The workshop addressed three ways we can use paleoenvironmental data to gain a better understanding of climate change and its effects:

- To serve as a retrospective baseline for interpreting past and projecting future climate-induced environmental change.

- To differentiate the influences of climate and humans on past environmental change.

- To improve ecosystem management and restoration practices in the future.

Many current land-management and environmental-restoration practices tend to rely on meteorological records. Growing evidence of rapid rates of Late Quaternary climate change and projections of global climatic variation in the near future exceeding the historic record suggest that these practices are short sighted. The ecologically short duration of meteorological records may bias interpretations of how past human practices influenced present ecological conditions and how, in the future, ecosystems may respond to current practices.

Some computer models project that global climatic variation in the near future will exceed the meteorological record as a result of human-caused changes in the chemical composition of the lower atmosphere. Other models suggest that the Earth may plunge into another ice age in the distant future in response to periodicity in orbital parameters. The global scale of these models is inadequate for regional interpretation. In contrast, proxy records of climate change not only provide regional windows on the past but also may portend the direction and magnitude of future regional change. In the Four Corners region, proxy climate records have been reconstructed from (among other sources) tree rings, packrat middens, pollen in sediments, isotope analyses, ancient animal dung, and human archaeological remains.

This workshop centered on the Four Corners region because of its rich natural and cultural resources, progressive land-management initiatives, well-developed paleoenvironmental records, and ongoing ecological resource-monitoring and environmental-restoration programs. Whereas livestock production and mining dominated the region's economy throughout much of the 20th century, now tourism and recreation are supplanting these more traditional land uses. Planning for the future depends, in part, on projecting ecological responses to this combination of land uses. Fortuitously, archaeologists have been developing proxy climate records for several decades to reconstruct changes in prehistoric ecology and agriculture that caused shifts in aboriginal populations. Ongoing ecosystem management initiatives and environmental-restoration programs can benefit from these records.

Almost all the natural, cultural, and recreational resources of the region are on lands managed by the U.S. Bureau of Land Management, the National Park Service, and the U.S. Forest Service. These agencies are cooperating with the U.S. Environmental Protection Agency on a pilot program (Ecosystem Monitoring and Assessment Program or EMAP) designed to assess the condition of ecological resources in the region. The goals of EMAP are to establish a baseline for monitoring trends and to develop innovative methods for anticipating environmental problems before they become widespread and irreversible. The paleoecological record can extend this time series as a means of contrasting climate-induced and human-induced trends now and in the future.

The Four Corners region was the center of uranium mining and milling during the 1940s, 1950s, and 1960s. Uranium was used for nuclear weapons production and nuclear power generation. The U.S. Department of Energy is in the process of cleaning up tailings at abandoned uranium millsites to reduce human health and environmental risks. Because some constituents of uranium mill tailings may remain hazardous for thousands of years, assessments are needed of the long-term performance of environmental-restoration practices. The paleoecological record can be used to assess possible long-term risks associated with changes in environmental processes that mobilize and transport hazardous tailings constituents.

Obviously, the potential uses of paleoecological data cross environmental disciplines. With this crossover in mind, we organized the workshop as a technical exchange forum for diverse researchers and practitioners who may otherwise rarely interact but share a common interest in the influences of climate change. Participants included climatologists, ecologists, archaeologists, land managers, environmental scientists, reclamation specialists, geologists, hydrologists, and engineers (see Appendix A for a list of workshop participants). This workshop was also organized as the first in a series. As such, the specific aims of the workshop were fundamental in nature:

- ***Initiate dialogue between researchers and end users of paleoclimatic data.*** This dialogue was achieved with presentations by researchers on paleoclimate sources and analytical methods and with presentations by end users on the data needs for environmental restoration and ecosystem management. Most of the presentations addressed paleoclimatic data sources and methods.

- ***Address areas of uncertainty associated with the assimilation and interpretation of paleoecological records.*** Areas of uncertainty are associated with inferences as to possible future climate-induced environmental change as well as past climate change. Figure 1 was presented to participants at the onset of the workshop to illustrate continuity between the past and the future, the researcher and the end user, and paleoclimate reconstruction methods and ecosystem management needs. The title, "Through a Mirror, Darkly," borrowed from Thomas Slater's paper (pages 145 through 161), reflects uncertainties in the process.

- ***Propose reasonable applications of current paleoclimate information and identify future research needs.*** A few presentations addressed applications of current paleoecological records. More critical evaluations of proposed applications are needed.

- ***Set in motion plans for future interaction.*** Participants agreed at the close of the workshop that the forum was informative and worthwhile. Two means for continued interaction were suggested: establish an Internet bulletin board for informal communication and convene subsequent workshops, possibly at U.S. Department of Energy facilities in other regions.

To achieve these goals, we organized the workshop into four sessions. The first two sessions covered paleoclimate data sources, reconstruction methods, and rates and magnitudes of climate change during

THROUGH A MIRROR, DARKLY

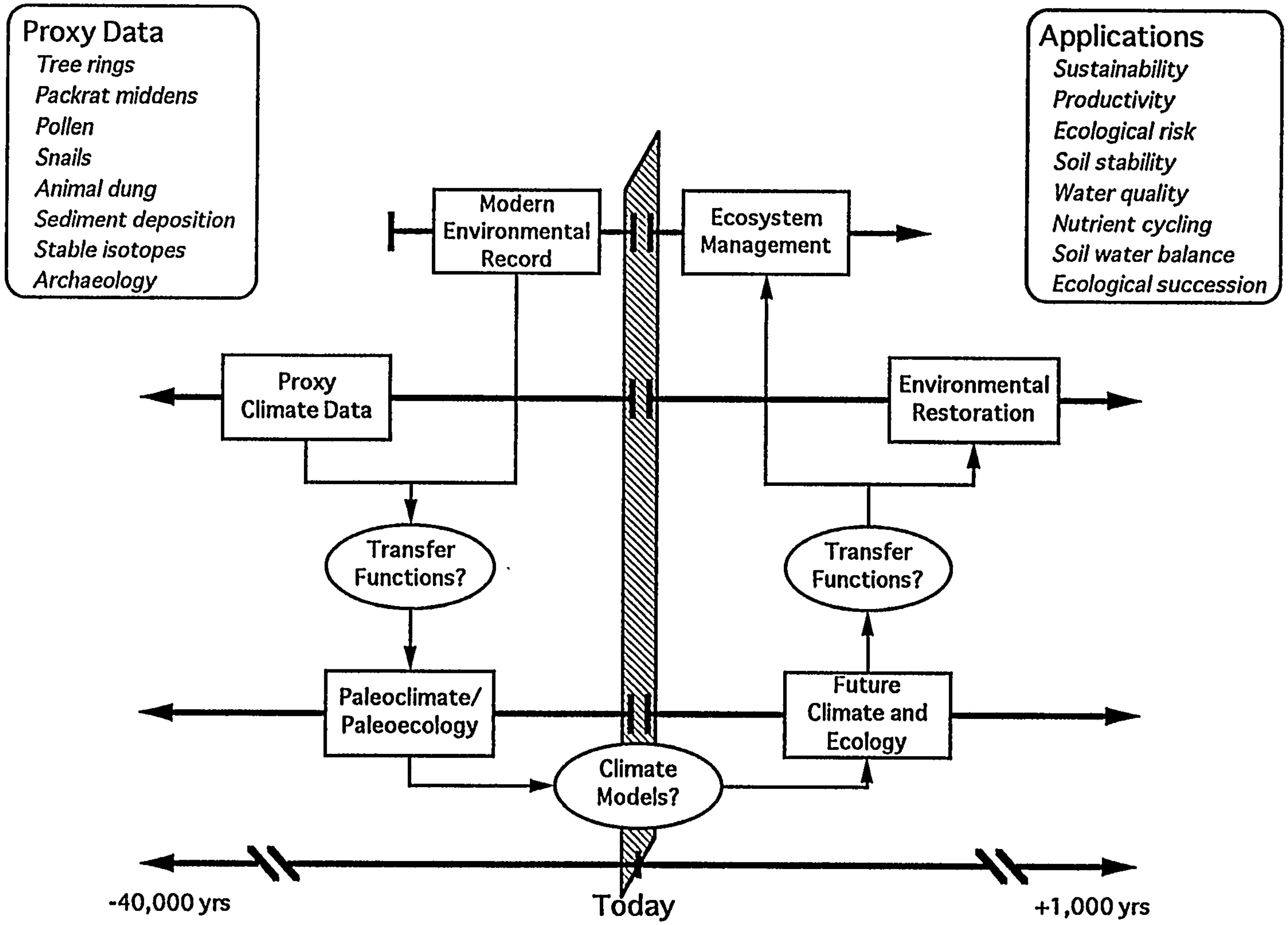

Figure 1. Proposed paradigm for using proxy records of past changes in climate and ecology as clues for ecosystem management and environmental restoration today.

the Pleistocene and Holocene. Session I (pages 1 through 38) focused on the Pleistocene and Session II (pages 39 through 82) emphasized Holocene data. Session III (pages 83 through 139), "Climate Change and Past Cultures," documented past climatic fluctuations that affected human populations and the use of this information as a long-term baseline for evaluating present-day climate and estimating future climatic trends. A paper by Nolan Doesken and Thomas McKee (pages 125 through 139) presented the instrumental record not only as a measure of present climatic variation but also as a reference to compare climates of the past and to envision climatic conditions of the future. Session IV (pages 141 through 185) concluded the workshop with presentations on how climate-change information can be used for land management and environmental restoration. Panel discussions led by a facilitator followed each session with session speakers serving as panel members. Appendix A lists the authors who presented papers and the conference attendees. A postworkshop field trip visited paleoclimate study sites and environmental-restoration projects within and near Arches and Canyonlands National Parks in Utah (see Appendix B for tour agenda).

ACKNOWLEDGMENTS

We thank the authors for their informative and timely contributions to these proceedings and for promoting the interdisciplinary theme of the workshop. We also thank all who contributed to planning and convening the workshop. In particular, we thank Peter Wigand and the Desert Research Institute for responding to our pleas for help; Russ Walker and Mesa State College for arranging facilities and logistics; Saxon Sharpe for organizing tour stops at Arches and Canyonlands; Mary Jane Price and Marilynne Gossett for formatting manuscripts; and Dennis DuPont, Jill Frantz, and Cheri Bahrke for making it all run smoothly.

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Session I: Paleoclimatic Data—Pleistocene

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DOCUMENTED QUATERNARY CLIMATE CHANGE ON THE COLORADO PLATEAU: 40,000 YR B.P.–PRESENT

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Keywords: *climate, Colorado Plateau, paleoclimate, paleoenvironmental, Quaternary*

ABSTRACT

Ten years of interdisciplinary research on the Colorado Plateau have produced numerous, complimentary data sets documenting environmental change over the past 40,000 years. Radiocarbon controlled chronologies allow the correlation of multiple data sets, providing an increasingly broad spectrum of environmental changes within this interval. Data sets include documentation of the presence of extinct fauna; discovery and analyses of dung deposits from extinct Pleistocene fauna; packrat midden studies; insect analyses; snail analyses; and alluvial chronologies. The results presented will be considered preliminary, as we have on-going field and laboratory studies.

INTRODUCTION

Research conducted in the past decade has demonstrated the existence of multiple Quaternary data sets which singly, and in concert, provide unparalleled paleoenvironmental/paleoclimatic records for the past 40,000 years (and older deposits). These data sets are reinforced and supplemented by younger data sets, as one temporally enters the late Holocene to Historic time frames. Unique conditions of the Colorado Plateau have preserved these primary data sets. With analyses and additional research, the Colorado Plateau promises to provide unparalleled paleoclimate information (Figure 1).

Data Sets

As shown in Figure 1, there are several independent data sets which have differing chronologic spans. Of the data sets shown (Table 1), most are limited beyond 40,000 yr B.P. (the limit of ^{14}C dating), however thermoluminescence (TL) dates have been obtained from stratified sedimentary units, yielding pollen, at greater than 100,000 yr B.P. Ancient alluvial deposits disclose a cyclic sequence of degradation (cuts) and aggradation (fills) for at least $\pm$ 40,000 years. Repetitive sequences of flood deposits indicate even older cycles, as well as major mass wasting events.

Geomorphic and hydrologic changes brought about by cycles of erosion and deposition altered local habitats, both creating and destroying relatively lush prehistoric habitats. These same habitats contain the remains and dung deposits of extinct Pleistocene megafauna such as mammoths, horses, camels, at least two varieties of sloths, shrub oxen, mountain goats, and at least one group that survived to historic times on the Plateau, bison.

The very presence of large grazers suggests relative abundance of grasslands and phreatic plants such as rushes and sedges. The micro analyses of dung from the extinct animals gives us a glimpse of the plants available for consumption. That, in turn gives us a method to

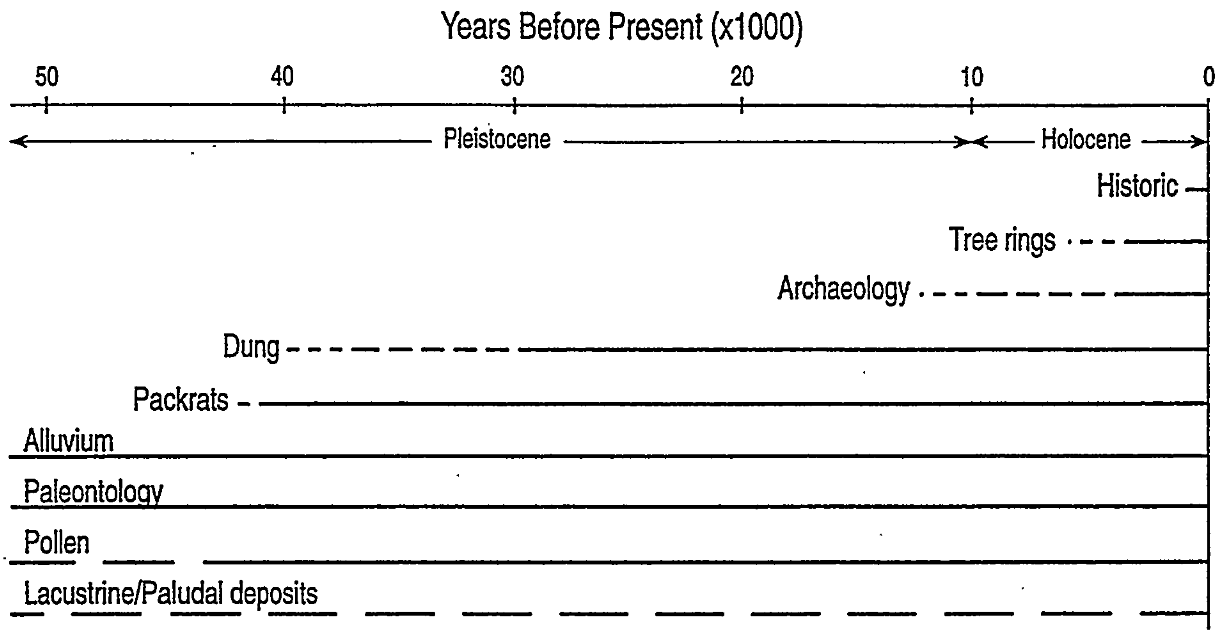

Figure 1. Primary Data Sets and Their Temporal Ranges: Colorado Plateau

reconstruct moisture and temperature conditions at intervals dated by radiocarbon. Secondarily, analyses of dung of grazers, versus browsers, versus animals that graze <u>and</u> browse gives a broader view of reconstructed plant communities.

Applying such reconstructions to temporal intervals, say 500 to 1000 year intervals, should develop a model of vegetation change (and climate change) through time; at least for a given locality. A network of such locality reconstructions can produce a regional model which can be carried to modern times.

A second, independent set of information can be derived from analyses of packrat middens in the same locations, for the same temporal periods. Two sets of botanical information—from different data samples would provide an even broader reconstruction of the plant communities, and therefore the temperature and moisture (i.e., climate signal) of those time intervals.

At approximately 11,500–11,000 yr B.P. human presence on the Colorado Plateau has been documented (Agenbroad 1986a, 1986b; Agenbroad et al. 1990; Agenbroad and Mead 1990, 1992). The distribution of faunal remains of mammoths, the distribution of Clovis projectile points (mammoth hunters), and the distribution of proboscidean rock art leave little doubt as to the presence of Paleoindian mammoth hunters on the Colorado Plateau.

Similarly, the paleontological distribution of bison, the distribution of artifacts of bison hunters (Folsom and Plano cultures), and the distribution of bison rock art leave little room for argument for the presence of bison and Paleoindian bison hunters on the Colorado Plateau during the interval of 10,000 yr B.P. to 6000 yr B.P.

Increasing evidence of Archaic cultural presence from ± 8000 yr B.P. to the beginnings of horticulture and semi-sedentary to totally

Table 1. Paleoenvironmental Data Sets Used To Construct a Geochronologic and Paleoenvironmental Framework (from Agenbroad and Mead 1989, 1990, 1991, 1992, 1993 NPS reports)

TEMPORAL INTERVAL	PALEONTOLOGIC	ARCHEOLOGIC	GEOLOGIC	HYDROLOGIC
pre-11,000 B.P. (9,000 B.C.)	extinct fauna: mammoth, horse, camel, shrub oxen, sloths, mountain goat	Paleoindians: Clovis projectile point 	cut and fill (erosion) color and texture of sediment guide fossils (vertebrate and invertebrate) soils sand dunes	cut and fill (erosion/deposition) oxidizing/reducing environment water table position lacustrine/paludal deposits invertebrates and amphibians
		Folsom projectile point 		
11,000 B.P. (9,000 B.C.) to 7,000 B.P. (5,000 B.C.)	absence of extinct fauna (modern fauna present)	Paleoindians: Plano cultures 	cut and fill (erosion) color and texture of sediment guide fossils (vertebrate and invertebrate) soils sand dunes	cut and fill (erosion/deposition) oxidizing/reducing environment water table position lacustrine/paludal deposits invertebrates and amphibians
		Early Archaic cultures 		
7,000 B.P. (5,000 B.C.) to 2,000 B.P. (0 B.C.)	absence of extinct fauna (modern fauna present) domestic ? forms	absence of Plano middle and late Archaic cultures	cut and fill (erosion) color and texture of sediment guide fossils (vertebrate and invertebrate) soils sand dunes	cut and fill (erosion/deposition) oxidizing/reducing environment water table position lacustrine/paludal deposits invertebrates and amphibians
2,000 B.P. (0 B.C.) to 0 B.P. (1950 A.D.)	absence of extinct fauna (modern fauna present) domestic ? forms	ceramics, Basketmaker and Pueblo artifacts 	cut and fill (erosions) color and texture of sediments guide fossils (vertebrate and invertebrate) soils sand dunes	cut and fill (erosion/deposition) oxidizing/reducing environment water table position lacustrine/paludal deposits invertebrates and amphibians

Table 1 (continued). Paleoenvironmental Data Sets Used To Construct a Geochronologic and Paleoenvironmental Framework (from Agenbroad and Mead 1989, 1990, 1991, 1992, 1993 NPS reports)

CHRONOLOGIC	PALYNOLOGIC	MACROBOTANICAL	MALACOFAUNA	ENVIRONMENTAL AND PALEOCLIMATIC INTERPRETATIONS
buried organic remains charcoal as sediment buried cultural features (hearths) fossils packrat midden chronology	chronologically controlled pollen profiles	plant remains dung packrat middens	Boreal-mesic species	interpret fossil vs. modern communities of plants and animals Infer temperature and moisture condition Describe geologic processes at work in the temporal interval
buried organic remains charcoal as sediment buried cultural features (hearths) fossils packrat midden chronology	chronologically controlled pollen profiles	plant remains dung packrat middens	Fewer number of boreal species; ponding phases	interpret fossil vs. modern communities of plants and animals Infer temperature and moisture condition Describe geologic processes at work in the temporal interval plus new cultural adaptions
buried organic remains charcoal as sediment buried cultural features (hearths) fossils packrat midden chronology ceramics for relative dates	chronologically controlled pollen profiles	plant remains dung packrat middens	Spotty records of mesic species indicating local ponding phases	interpret fossil vs. modern communities of plants and animals Infer temperature and moisture condition Describe geologic processes at work in the temporal interval plus new cultural adaptions presence or abandonment of areas previously occupied
buried organic remains charcoal as sediment buried cultural features (hearths) fossils packrat midden chronology ceramics for relative dating	chronologically controlled pollen profiles evidence of cultigens	plant remains dung packrat middens evidence of cultigens	Spotty records of mesic species indicating local ponding phases	interpret fossil vs. Modern communities of plants and animals Infer temperature and moisture condition Describe geologic processes at work in the temporal interval plus new cultural adaptations presence or abandonment of areas previously occupied

sedentary life styles by ± 700 yr B.P. has been well documented. The contraction from, or abandonment of most of that cultural area has most commonly been attributed to climatic change.

Historic records of meteorological data, floral and faunal records, land use (and misuse), soil types, and distribution often has little relevance to the preceding 40,000 to 1000 years of plateau history.

UNIQUE CONDITIONS ON THE COLORADO PLATEAU

The semi-arid to arid conditions prevailing on most of the Colorado Plateau has allowed "perishables" to be preserved. Items such as condor nests, feathers, eggshells, chicks; extinct animal remains with hair, horn sheaths, skin, tissue, dung, etc., are examples of data sets not present in most other regions of the planet—outside the permafrost regions of high latitudes.

These features plus abundant materials which can be dated by radiocarbon, to provide a tightly controlled chronology of samples, and therefore events, are unique to the Plateau. The presence of multiple, independent data sources provides a more realistic final model, than that derived from one set of information, alone.

Dung deposits not only testify to animals and plants present at a locality, they also serve as deposits in which insects, which were present when the dung was fresh, have been preserved. In a similar manner, snails provide evidence for past hydrologic systems, but have been little studied across the Colorado Plateau.

SYNTHESES AND RESULTS OF INVESTIGATIONS SINCE 1980

Several fundamental hypotheses have been formulated for the Colorado Plateau for the past 40,000 years.

1) There has been a demonstrated retreat (up-gradient/up-latitude migration of botanical communities on an absolute time scale (at least for the last 11,000 years).

2) Late Pleistocene faunal communities were widespread but at or about 11,000 yr B.P. became disfunctional or extinct.

3) At approximately 11,500 to 11,000 years ago human presence has been documented on the Colorado Plateau, increasing to a maximum population density between A.D. 1200 to A.D. 1300, then declining to modern populations.

4) The Colorado Plateau provides a unique "Past–Present–Future" model for climate change.

ACKNOWLEDGMENTS

The results synthesized in this paper are the preliminary interpretations of more than a decade of field and laboratory research. Sponsors for this research include: The National Park Service, The National Geographic Society, Northern Arizona University, The Bureau of Land Management, and the National Forest Service.

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LATE GLACIAL ARIDITY IN THE SOUTHERN ROCKY MOUNTAINS

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Keywords: *palynology, Rocky Mountains, late glacial, aridity, sagebrush*

ABSTRACT

While the slopes of the present-day Colorado Rocky Mountains are characterized by large stands of subalpine and montane conifers, the Rockies of the late glacial looked dramatically different. Specifically, pollen records suggest that during the late glacial [15–11 ka], *Artemisia* and Gramineae predominated throughout the mountains of Colorado. At some point between 11,000 and 10,000 B.P., however, both *Artemisia* and grasses underwent a dramatic decline, which can be identified in virtually every pollen diagram produced for Colorado mountain sites, including Como Lake (Sangre de Cristo Mountains), Copley Lake and Splains Gulch (near Crested Butte), Molas Lake (San Juan Mountains), and Redrock Lake (Boulder County). Moreover, the same pattern seems to hold for pollen spectra derived for areas adjacent to Colorado, including at sites in the Chuska Mountains of New Mexico and in eastern Wyoming. The implications of this consistent finding are compelling. The closest modern analogues to the *Artemisia*- and Gramineae-dominated late-glacial Colorado Rockies are found in the relatively arid northern Great Basin, which suggests that annual precipitation was much lower in the late-glacial southern Rocky Mountains than it was throughout the Holocene.

INTRODUCTION

There has been considerable discussion and disagreement in the literature over the reconstruction of precipitation regimes for the southern Rocky Mountains during the late glacial, approximately 15,000 to 11,000 years B.P. A few researchers have suggested that this was a time of increased annual precipitation, while others have argued that the period was drier than either the preceding full glacial or the Holocene. We propose that a review of pollen diagrams from Colorado Rocky Mountain sites provides credence for the latter view, that the late glacial was relatively arid.

Colorado pollen spectra consistently show high percentages of *Artemisia* and Gramineae until sometime between 11,000 and 10,000 B.P., at which point the percentages drop precipitously. Contrary to the view of Maher (1972) and others (Carrara et al. 1984), we do not believe that *Artemisia* is over-represented in the samples, but rather that it reflects a genuinely significant presence of sagebrush at high altitudes. The predominance of sagebrush and grasses in the Colorado samples is viewed as analogous to modern vegetation in the relatively arid (Houghton et al. 1975) northern Great Basin. We argue that the high percentages of *Artemisia* and Gramineae in the late-glacial southern Rockies indicate an arid environment there as well.

This paper will first discuss interpretations of the late glacial in Colorado as a relatively moist period. Next, hypotheses proposed to explain high percentages of non-arboreal pollens in the late glacial are reviewed. Finally, we present pollen diagrams that show the high representation of *Artemisia* and Gramineae up to approximately the Pleistocene-Holocene boundary, and we reiterate that they are indicative of an arid late glacial.

ARGUMENTS FOR A MOIST LATE GLACIAL

Paleoecological reconstructions have been attempted for locales throughout Colorado (see Fig. 1 for sites mentioned in this paper), including the southwest (e.g., Andrews et al. 1975; Carrara et al. 1984; Maher 1961; Petersen and Mehringer 1976), south-central (e.g., Davis and Shafer 1991; Jodry et al. 1989; Shafer 1989); central (e.g., Fall 1988; Markgraf and Scott 1981), and Colorado Front Range (e.g., Legg and Baker 1980; Maher 1972). As noted above, however, these reconstructions vary in the paleoecological pictures they paint of the last 15,000 years, including the late glacial.

According to Petersen (1981), for example, the period from about 13,500 to 12,000 B.P. in the San Juan Mountains was characterized by a lower elevational limit of spruce and Douglas fir, from which he infers that (1981:134) "there was more annual precipitation to offset greater evaporation due to warmer summer temperatures." The increased precipitation, he argues, would have resulted from a combination of a more southerly storm track (due to the presence of ice sheets to the north) and increased water in the atmosphere as a function of melting ice and warming sea surface temperatures. He cites as evidence the work of Van Devender and Spaulding (1979), who argue that the Cordilleran ice sheet, among other variables, contributed to intensification of the Aleutian low, which would indeed have caused "increased frontal precipitation between 14,000 and 8,000 B.P." (Petersen 1981:139). However, Van Devender and Spaulding (1979:708) clearly point out that this applies to regions "south of the crest of the Sierra Nevada (36 degrees N) and as far east as Trans-Pecos Texas," which leaves out Colorado. Moreover, in discussing the northern Mojave and Great Basin Deserts, Spaulding et al. (1983:288) note that

> in contrast to the warm deserts [further south], there is little biotic evidence for a marked increase in average precipitation (Cole 1982; Spaulding 1981). The discovery that most playas of southern and south-central Nevada were, at best, ephemeral lakes or marshes during the full glacial (Mifflin and Wheat 1979) also points to relatively dry conditions north of latitude 36 degrees N (Van Devender and Spaulding 1979).

Nelson et al. (1979:413), like Petersen, but based upon work at the Mary Jane Site in the Fraser Valley, Colorado Front Range, also interpret the late glacial as a relatively moist period. They characterize their "peat K," which is bracketed by radiocarbon dates of 13,740 + 160 (DIC–671) and 12,380 + 180 (DIC–516), as representing first "cold and wet?" conditions, and then conditions "similar to present." These climatic interpretations are based upon three successive vegetation regimes in the bracketed period which they term "dry herb and sedge tundra," then "successional spruce-fir forest; open ground herbs," and finally "spruce-fir-pine forest; dry ground herbs." Madole (1986), however, has questioned this interpretation. He points out and evidently finds troublesome that unlike virtually all other Colorado pollen records, the Mary Jane Site shows only a small percentage of *Artemisia* during the full glacial. It would seem prudent, therefore, to view the Nelson et al. (1979) interpretations with some caution.

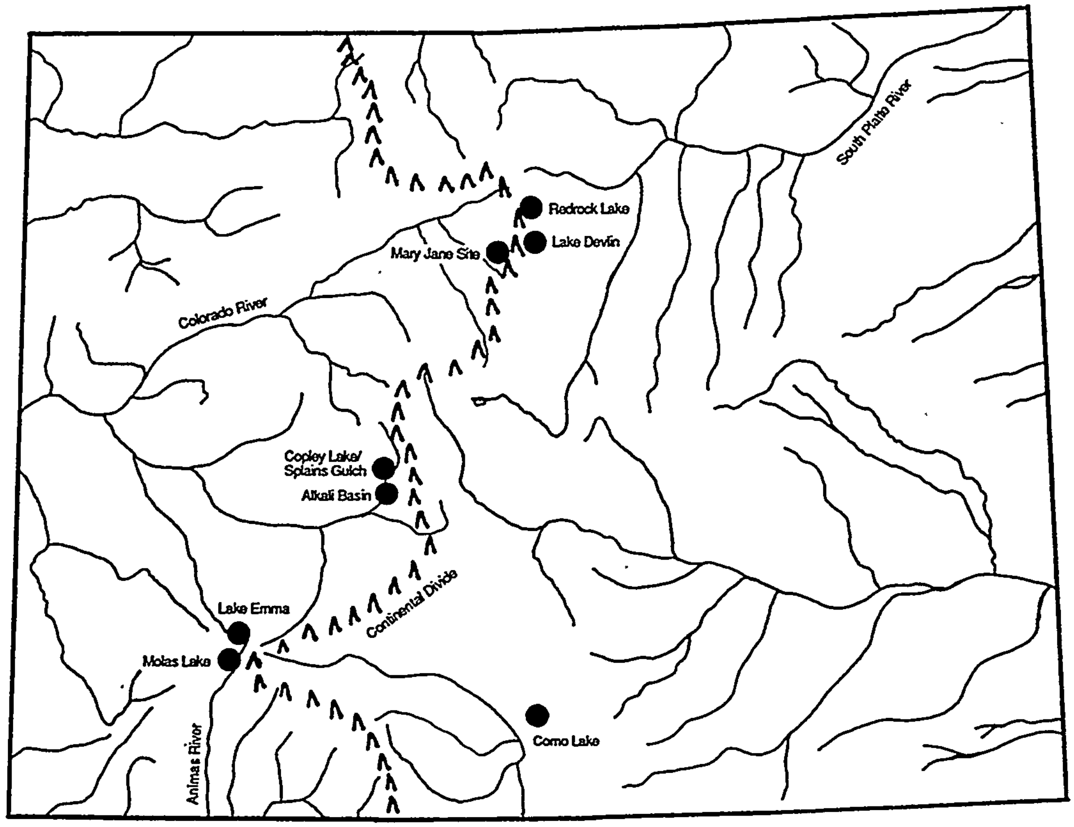

Figure 1. Map of Colorado Showing Key Sites for Paleoclimatic Reconstruction

In addition to Petersen's work in southwestern Colorado and Nelson et al.'s in the Front Range, pollen from another Colorado site has been characterized as representing a moist late glacial. In the Alkali Creek basin near Gunnison, Colorado, a pollen assemblage dating to 12,975 ± 430 B.P. (GX-6794) showed high levels of pine and spruce pollen, but low levels of shrub and herb pollen, "representing cold, moist subalpine conditions with an estimated annual precipitation of at least 90 cm (40 in) and a mean July temperature at or below about 12 degrees C (53 degrees F)" (Markgraf and Scott 1981:233). Importantly, though, this site is located in a high-altitude basin, unlike the majority of Colorado locales for which pollen profiles have been derived, and it is likely that the high percentages of conifers there are representative of a well-watered microenvironment and not a broad ecological trend.

In fact, most Colorado investigations have yielded evidence suggesting that if there was a broad ecological trend during the late glacial, it was probably toward aridity. Most importantly, the vast majority of locales, including Molas Lake (Maher 1961) and the Mary Jane Site (Nelson et al. 1979), both of which Petersen incorporates into his interpretation of a moist late glacial, show high percentages of *Artemisia* and sometimes Gramineae pollen, which we consider to be indicative of dry conditions. Before evaluating these sites in detail, however, the various proposed implications of high percentages of these non-arboreal pollens are discussed.

HYPOTHESES EXPLAINING HIGH LATE GLACIAL *ARTEMISIA* PERCENTAGES

Maher (1961, 1963, 1972) has hypothesized that at both San Juan Mountain cirque lakes and at Redrock Lake in the Front Range, pollens are differentially represented in sediments due to topographic factors. Specifically, he argues that pollen from plants flowering early in the spring, which includes most trees, would accumulate on still-frozen lakes, only to be flushed away by melting snow later in the spring (a process that would have been enhanced during the late glacial, when there was more snow). Plants flowering later in summer, like *Artemisia*, however, would be trapped in the thawed lakes, and incorporated preferentially into sediment.

This mechanism has been rejected, however, by Patricia Fall (1988) for the late glacial in the Southern Rocky Mountains. She points out that high *Artemisia* pollen percentages have been found in late glacial packrat middens on the Colorado Plateau, where lake flushing could not have occurred. She cites a study by Betancourt and Davis (1984), for example, which revealed (Fall 1988:270) "38% *Artemisia* pollen from a packrat midden dated at 11,900 yr B.P. from Canyon de Chelley (at 1770 m) just below the Chuska Mountains."

A second explanation for the disproportionately high presence of *Artemisia* during the late glacial in the southern Rockies is offered by Wright et al. (1973:1173), who propose that "alpine herbs in general are low pollen producers, so that alpine *Artemisia* species . . . can be represented in the pollen counts at much higher percentages than in counts of the plants themselves." As Fall (1988:271) notes, Legg and Baker (1980) support this hypothesis, inferring that at Lake Devlin, northern Colorado, high pollen influx values do suggest that *Artemisia* was present during the late glacial, but as alpine plants. Carrara et al. (1984) likewise believe that high percentages of sagebrush at Lake Emma in the San Juan Mountains are indicative of alpine tundra and herbaceous species of *Artemisia*. However, *Artemisia* percentages in contemporary alpine vegetation never exceed 25% (Fall 1992).

Whereas proponents of both of the preceding hypotheses question whether *Artemisia* pollen might be over-represented in high altitude samples dating to the late glacial, others (Barnosky 1985; Bent and Wright 1963; Fall 1984; Mehringer et al. 1977) accept the high ratios as reflecting wider ranges of sagebrush steppe in the past. This is a significantly different scenario than that posed by Wright et al. (1973) above, who note that the *Artemisia* could be overshadowing pollen indicative of a tundra environment. Fall (1988:271–2) addresses this issue of whether the late-glacial Colorado Rockies were steppe or alpine tundra, but ultimately concludes that the question cannot currently be resolved in North America.

We do not subscribe to the belief that the high percentages of *Artemisia* about to be discussed for sites in the mountains of Colorado are the product of over-representation by any mechanism. Rather, we believe that they reflect a very real late-glacial abundance of *Artemisia*, likely *Artemisia* tridentata. The northern Great Basin, which is itself dominated by sage, can be viewed as a modern analogue to the late glacial in the Colorado Rockies (Fall 1988). Based on modern precipitation values in that region, the *Artemisia* steppe of the late glacial could have persisted with only 15 to 20 cm of annual precipitation (Fall 1988; Houghton et al. 1975).

EVIDENCE FOR AN ARID LATE GLACIAL

Returning first to southwest Colorado, Maher's (1961) work at Molas Lake shows very high percentages of *Artemisia* pollen between 220 and 150 cm depth, but at 150 cm, the ratio decreases dramatically (Fig. 2). Maher interprets this change as representing the late glacial-post glacial boundary (1961: Fig. 16). However, he explains the high values of the

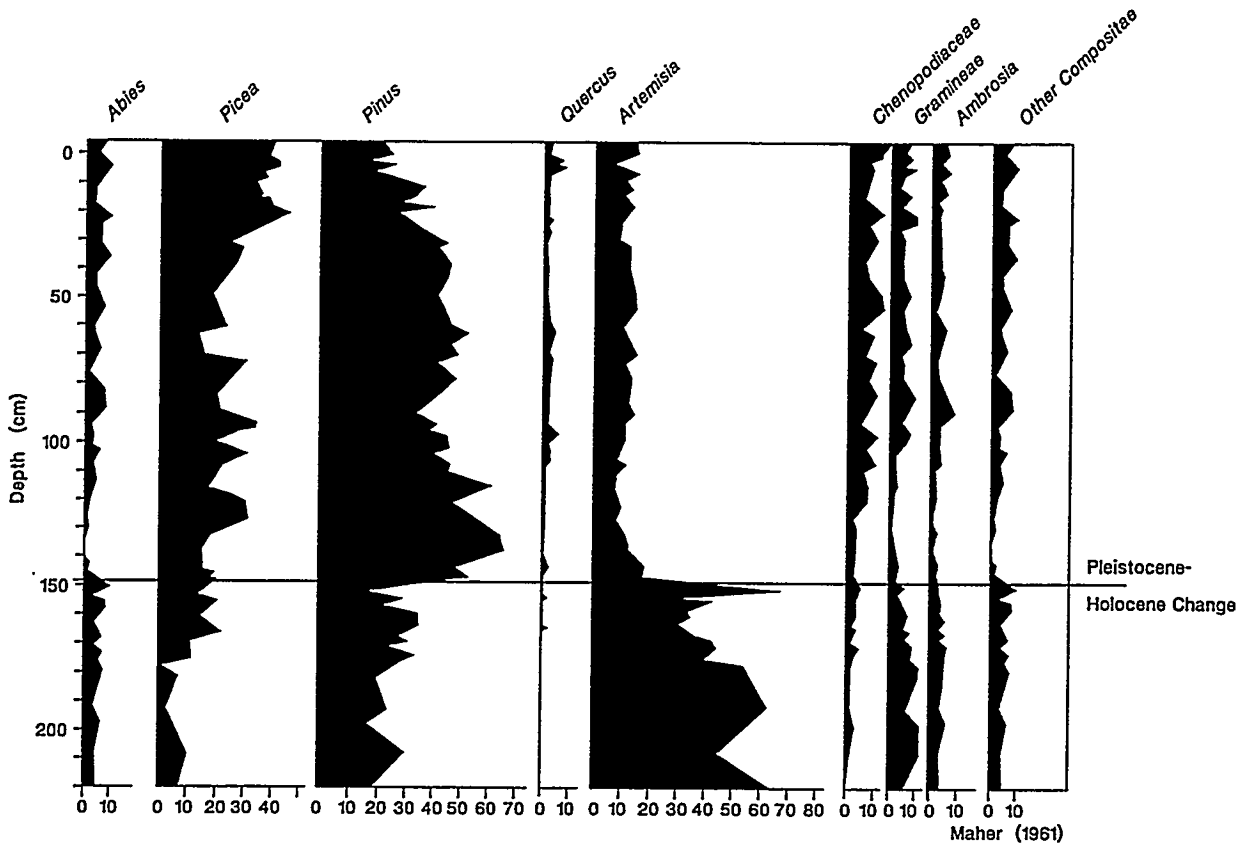

Figure 2. Pollen Percentage Diagram for Molas Lake, Northeastern Colorado, After Maher (1961)

late glacial in terms of the model discussed above, whereby summer-flowering plant pollen, primarily *Artemisia*, was differentially incorporated into lake sediments.

Petersen (1981:130) discusses the timing of the change in *Artemisia* values at Molas Lake, observing that the decrease occurred at about 13,350 B.P., rather earlier than the 10–11 ka time frame that we are proposing. However, the two radiocarbon dates obtained for Molas Lake organic sediment (Stuiver 1969:579) have always been viewed as suspect, by Maher himself among others, due to the potential for contamination by carbonate in the bedrock that underlies Molas Lake (James Benedict personal communication 1994; Fall 1988). If the dates are too old, as they would tend to be if this sort of contamination had occurred, then the change in abundance of *Artemisia* would have taken place at some time later than 13,350 B.P., possibly, as we are proposing, at about the Pleistocene-Holocene boundary.

In addition to Maher and Carrara et al.'s work, Andrews et al. (1975); Petersen (1975, 1981); and Elias et al. (1991) have also conducted palynological studies at sites in the San Juan and La Plata Mountains; however, their respective pollen spectra have basal dates of less than 10,000 B.P. and thus cannot shed light on the issue under question. The work by Elias et al. (1991) follows up on an earlier study by Carrara et al. (1984), which produced a basal radiocarbon date of 14,940 ± 140 (W-4525) at Lake Emma. The follow-up study demonstrates that this radiocarbon date was inaccurate, and that the Lake Emma pollen sequences illustrated in Carrara et al. (1984:50–51) are probably Holocene in age.

Fall's work at Copley Lake and Splains Gulch, near Crested Butte in central Colorado, also display *Artemisia* dominance in the late Glacial. At Copley Lake (Fig. 3), for instance, both *Artemisia* and Gramineae percentages are high at depths greater than 135 cm or so, which is radiocarbon dated to 10,325 ± 465 (GX-12996), but decrease sharply at a slightly greater depth, never again to reach such a high percentage. Splains Gulch sediments (Fig. 4) are radiocarbon dated to only 8560 ± 600 (A-2424), but the Splains Gulch pollen diagram shows clearly that just prior to that time (presumably between 11 and 10 ka), *Artemisia* did undergo a significant decline. Fall (1988:265–272) addresses the issue of late glacial vegetation, inferring from her data that

> Late-glacial vegetation in intermontane valleys consisted of cold periglacial steppe, with conifers restricted to drainages and rocky habitats below 2800 m elevation. Alpine tundra probably was more extensive than it is today (although the evidence from pollen analysis remains equivocal).

Three final examples of the *Artemisia*- and Gramineae-dominant late-glacial trend come from northern Colorado. For Redrock Lake near Boulder, Maher (1972) has reported a pollen spectrum with a basal radiocarbon date of approximately 9,760 B.P. Furthermore, using a calibration equation, he (1972:552) calculates that the base of the core dates to about 10,500 radiocarbon years old. In keeping with this interpretation, the pollen percentages (Fig. 5) again reflect an *Artemisia* and Gramineae predominance until about 10,000 B.P., at which point the percentages decrease to much smaller values. As for his Molas Lake sample, Maher again argues that the high percentages of sagebrush pollen at Redrock Lake reflect only differential deposition, and not a real difference in the presence of *Artemisia*.

Legg and Baker's (1980) work in Devlins Park consists of a palynological study of a core dating from just over 22 ka to about 14 ka, so it does not show the abrupt change at 11–10 ka that the other investigations do.

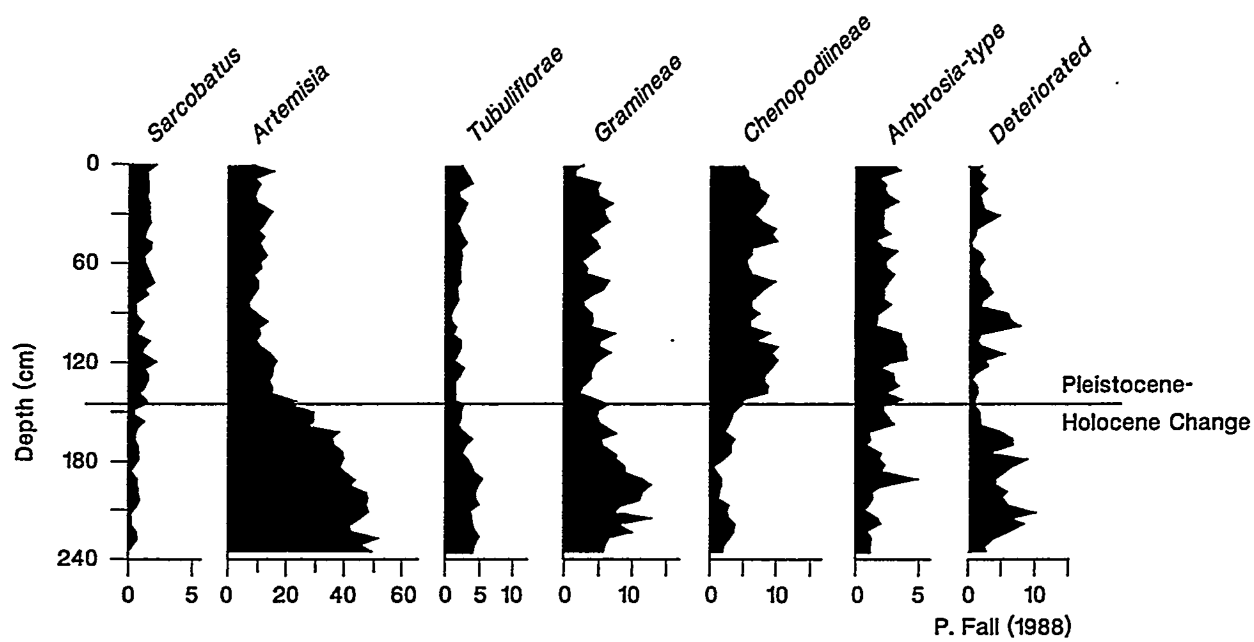

Figure 3. Pollen Percentage Diagram for Copely Lake, Central Colorado, After Fall (1988)

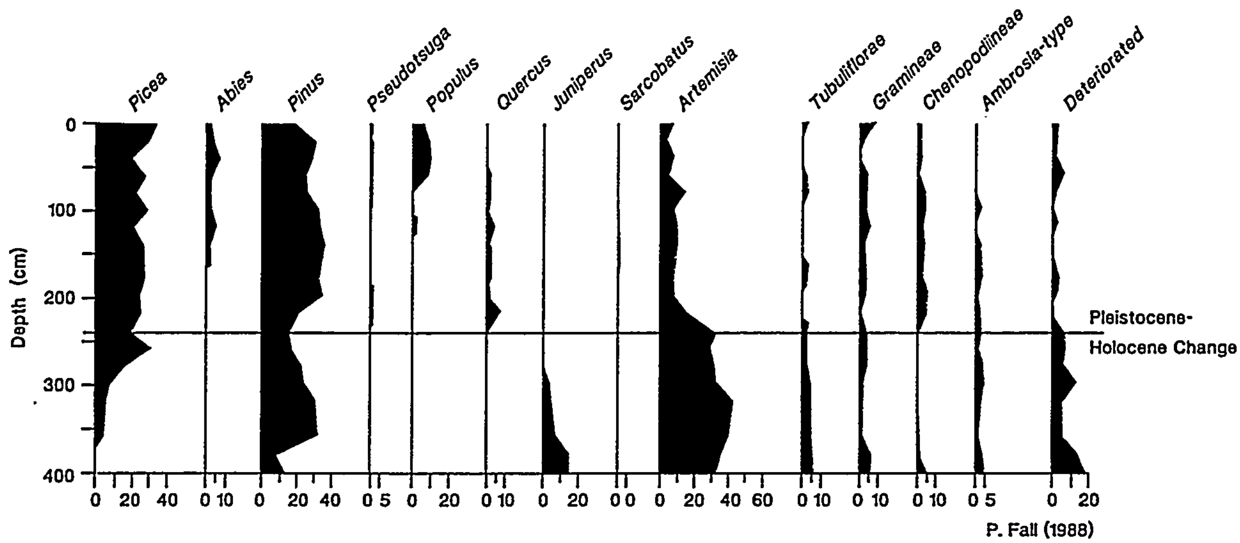

Figure 4. Pollen Percentage Diagram for Splains Gulch, Central Colorado, After Fall (1988)

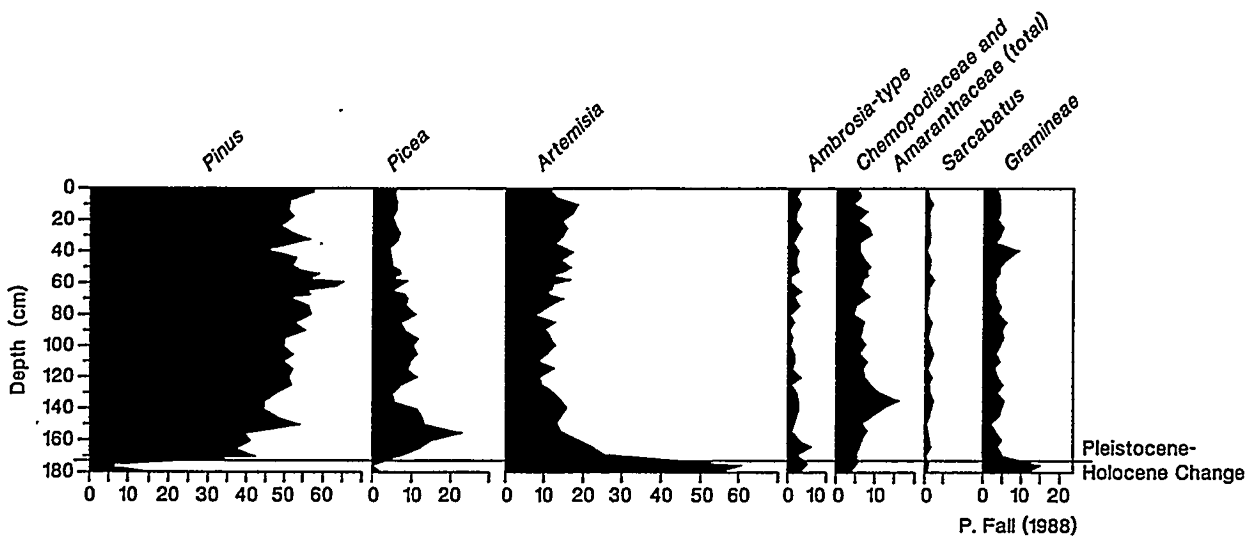

Figure 5. Pollen Percentage Diagram for Redrock Lake, North-Central Colorado, After Maher (1972)

Nonetheless, it does suggest yet again that *Artemisia* percentages were high throughout the full and late glacial. Similarly, a number of studies outside of Colorado proper also reenforce this thesis. For example, in zone 2 at Deadman Lake in the Chuska Mountains of New Mexico (Wright et al. 1973), which is estimated to date up to 13,500 B.P., values of non-arboreal pollen are high, "especially those of *Artemisia* (30 to 50 percent), suggesting a treeless landscape . . ."

A comparison of the fossil pollen at Como Lake (elevation 3669 m in the Sangre de Cristo Mountains) with contemporary pollen percentages illustrates our case for late-glacial aridity. Like Molas Lake (Maher 1961), Como Lake is in southern Colorado (Fig. 1);

and like Molas Lake, it shows very high percentages of *Artemisia* pollen during the late glacial—greater than 56% before 11,000 yr B.P. decreasing to just 10% after 10,500 yr B.P. (Fig. 6, Davis and Shafer 1991; Jodry et al. 1989; Shafer 1989).

The modern analogs for the late-glacial samples can be found throughout the northern Great Basin (Fig. 7). The similarity of the Como Lake samples to a database of 1200 contemporary pollen samples (Davis, in press) is computed using the squared chord distance dissimilarity statistic (Overpeck 1985). Most of the close analogs (squared chord distance < 0.15) are from central Washington (Mack and Bryant 1974) and central Nevada (Kautz 1983). Modern analogs also exist near Como Lake (Fig. 7), but these are in sagebrush steppe at low elevation (Fall 1992). In contrast, the contemporary analogs for the uppermost samples at Como Lake are nearly all from high-elevation localities in southern Colorado (Fig. 7, sites of Maher 1963; Fall 1992). Figure 8 compares the pollen percentages of the uppermost and lowermost Como Lake samples with their closest modern analogs. The closest analogs for the lowermost sample are from southern Colorado below 2500 m elevation (F33), and in the Columbia Basin in central Washington (W1–W17). Mean annual precipitation at these localities is less than 300 mm. In contrast, the modern analogs for the uppermost Como Lake samples are at high elevation, where mean annual precipitation is greater than 900 mm.

The high-*Artemisia* samples of the late glacial at Como Lake cannot be duplicated in modern alpine vegetation Rocky Mountains. Figure 9 contrasts the generally low percentages of *Artemisia* pollen (< 25%) in modern samples from alpine zone of the Rocky Mountains with the much higher percentages (> 40%) in high-elevation samples from the Great Basin. Thus, the high percentages of *Artemisia* in the late glacial do not necessarily indicate higher temperatures, because high *Artemisia* values can be found at high elevation in the Great Basin (Fig. 8). These Great Basin analogs do, however, suggest much greater aridity during the late glacial.

The phenomenon of high *Artemisia* percentages during the late-glacial extends northward into Wyoming and southern Idaho. At Rapid Lake in the Wind River Range of Wyoming, Fall (1988) reports *Artemisia* pollen percentages of 40 to 50% that drop to about 20% (Fig. 10) between 11,000 and 10,000 B.P. Gramineae pollen likewise decreases from 10–15% to less than 5%. Similar results have been reported for sites in Idaho (Davis 1981) and the Yellowstone Plateau (Baker 1983; Gennett and Baker 1986).

CONCLUSION

Clearly there is a significant degree of agreement between pollen sequences from throughout Colorado and surrounding areas when it comes to late glacial percentages of some nonarboreal pollens. Virtually all research shows extremely high percentages of *Artemisia* and sometimes Gramineae pollen during the late glacial, followed by dramatic decreases in both between 11 and 10 ka. Though some have argued that *Artemisia* is over-represented in the samples for various reasons, we draw the conclusion that these high late glacial levels are indicative of the very real presence of an extensive *Artemisia* steppe. Using the modern northern Great Basin as an analogue, this suggests that high-altitude Colorado was relatively arid during the late glacial.

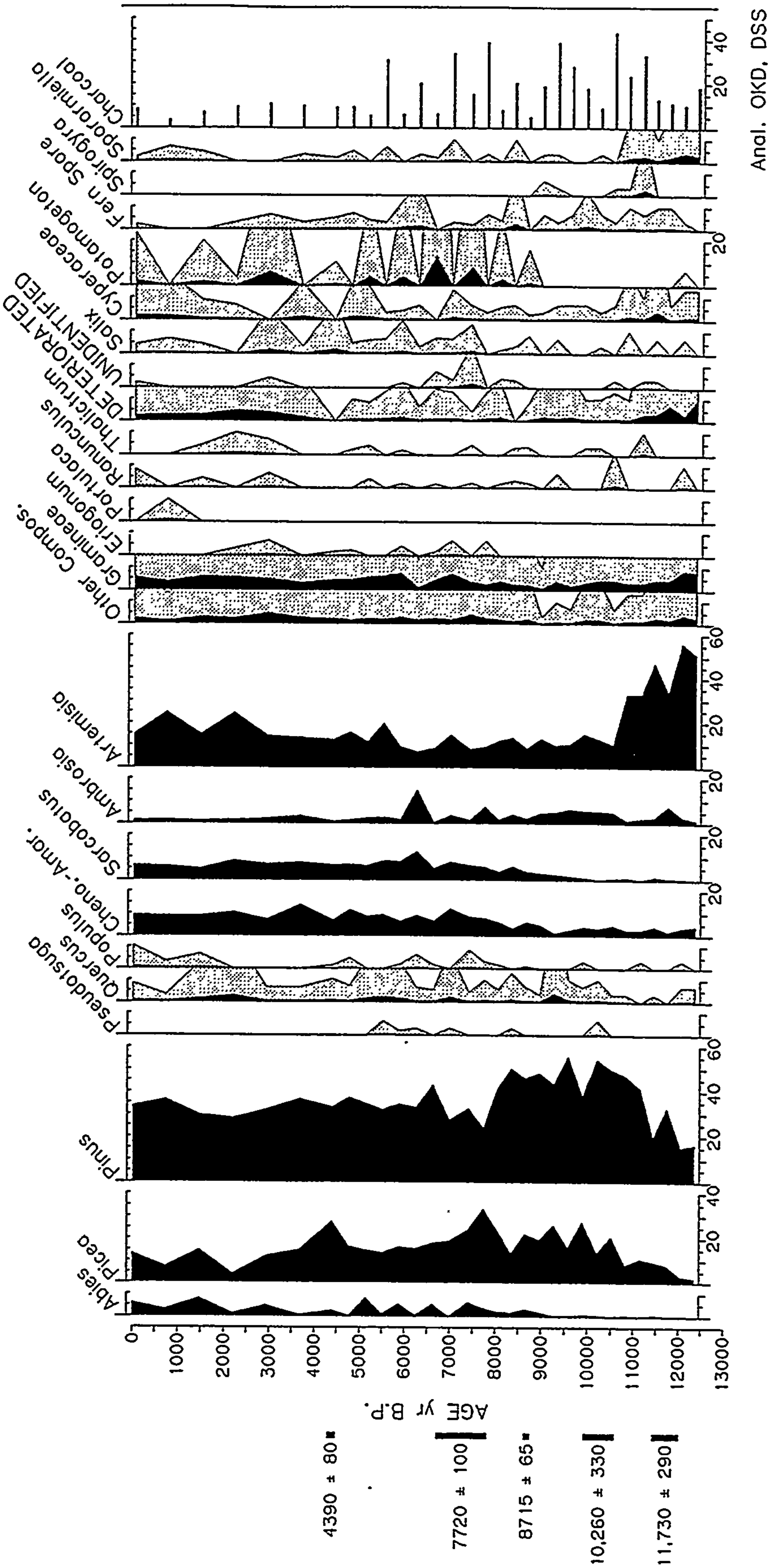

Figure 6. Pollen Percentage Diagram for Como Lake, South-Central Colorado

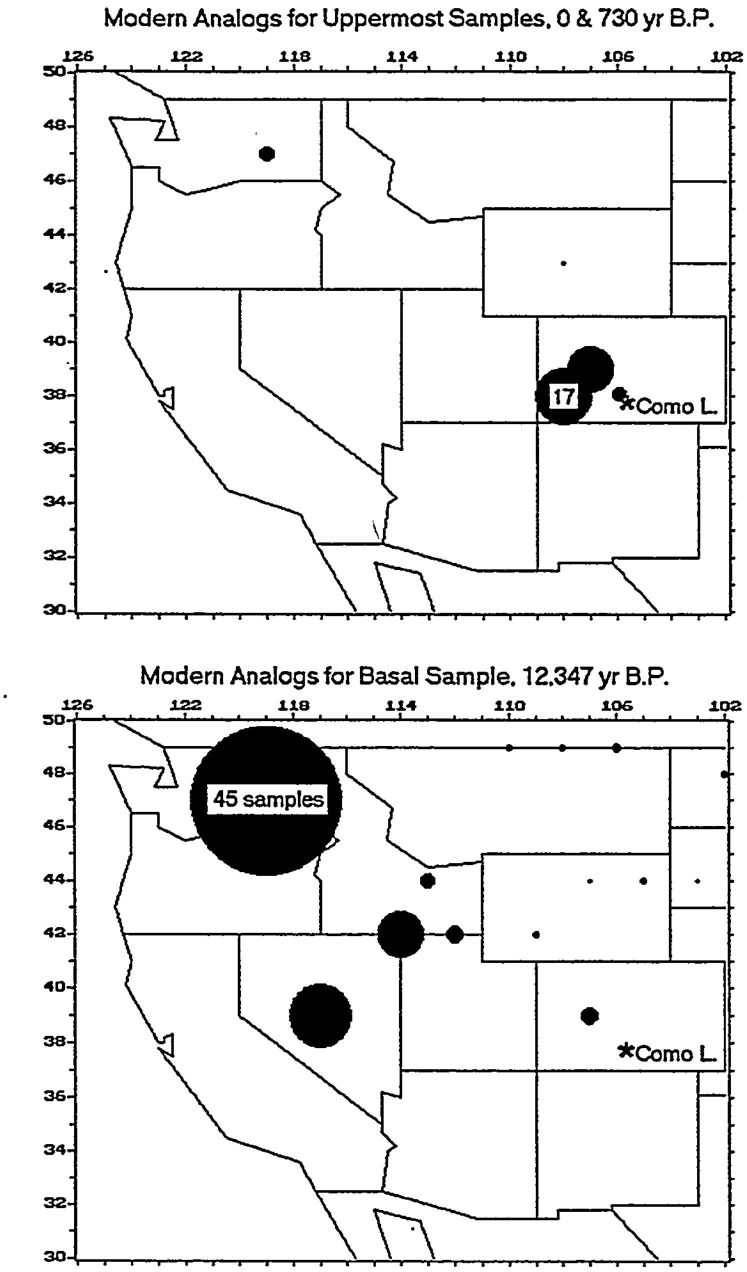

*Figure 7. Map of western North America showing location of modern analogs for contemporary and late-glacial (high-*Artemisia*) samples from Como Lake. Size of circle is proportional to number of samples that are modern analogs (squared chord distance < 0.15) at each site.*

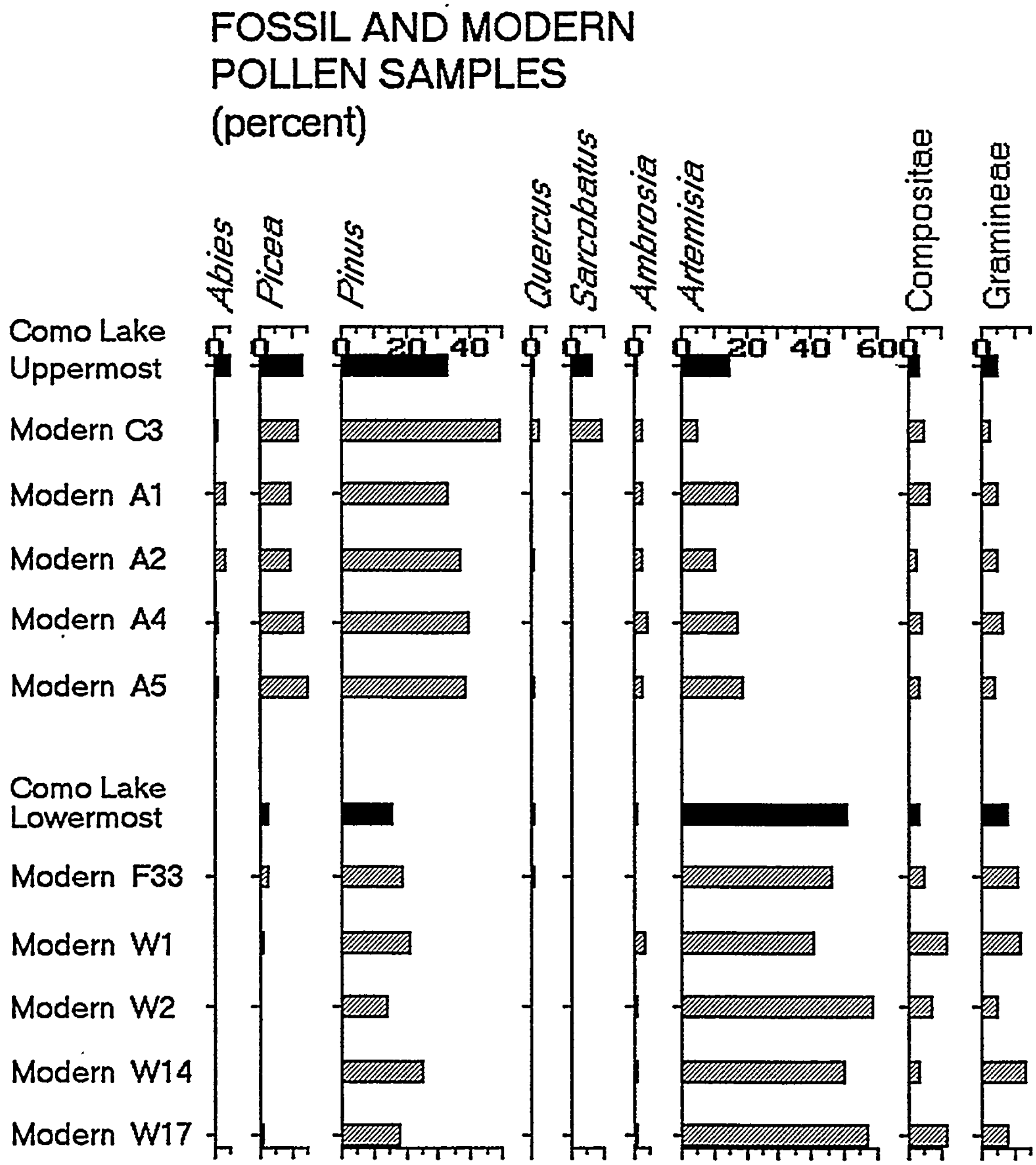

*Figure 8. Comparison of contemporary and late-glacial (high-*Artemisia*) samples from Como Lake with their closest modern analogs. C3—Como Lake (Shafer 1989); A1–A5—Animas, Colorado (Maher 1963); F33—central Colorado (Fall 1992); W1–W17—central Washington (Mack and Bryant 1974).*

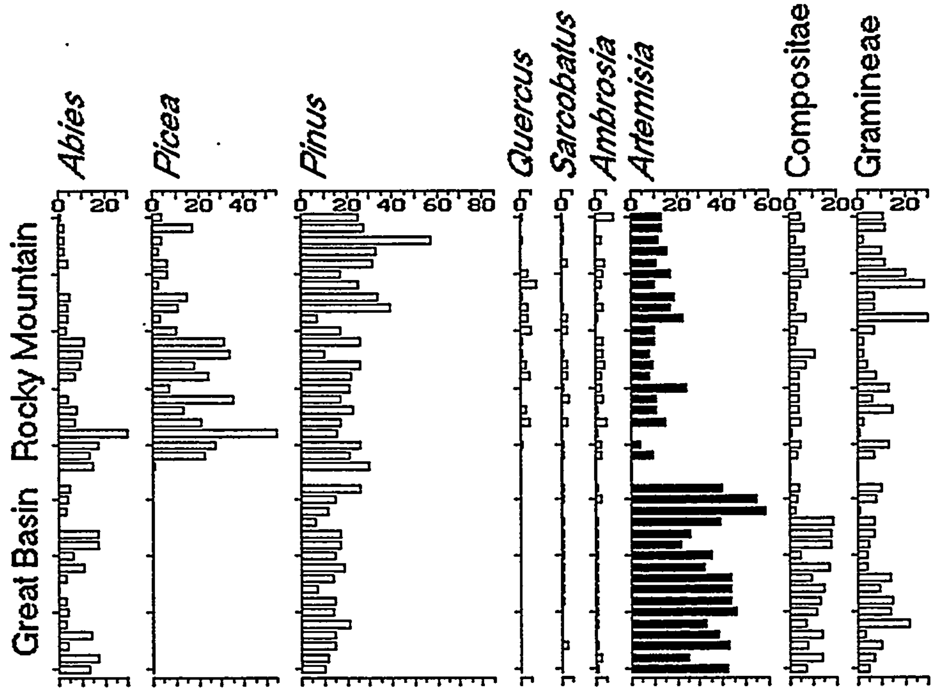

Figure 9. Comparison of Contemporary Pollen Samples From High Elevation in the Rocky Mountains and Great Basin

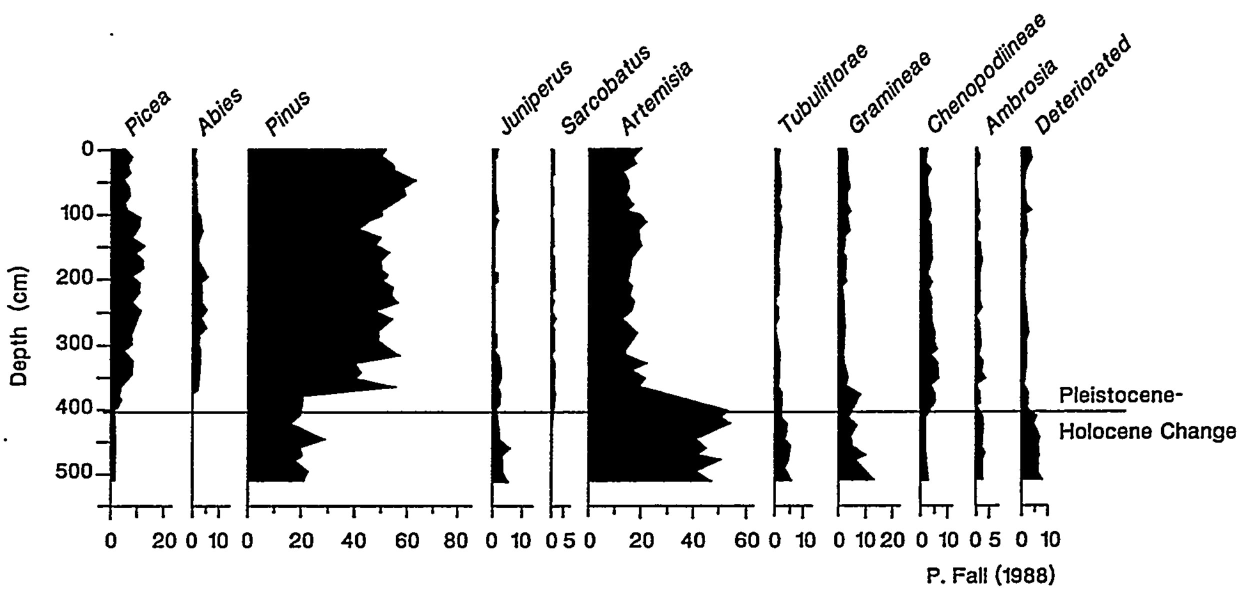

Figure 10. Pollen Percentage Diagram for Rapid Lake, Southern Wyoming, After Fall (1988)

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SNAILS, STABLE ISOTOPES, AND SOUTHWESTERN DESERT PALEOCLIMATES

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ABSTRACT

Modern and fossil molluscs (snails) occur in many localities in arid and semi-arid regions throughout the desert southwest. Live terrestrial snails are found under rocks and in forest litter and aquatic taxa inhabit springs, seeps, and/or wetlands. Molluscs uptake local water during their growing season (spring and summer) and incorporate its delta 180 signature into their shells. Preliminary 180 analysis of modern shells from the southern Great Basin indicates that the shells probably reflect meteoric water 180 values during the growing season. This provides a way to estimate the delta 180 value of precipitation and, thereby, the source of the moisture-bearing air masses.

Significant 180 variability in shells analyzed include geographic location, elevation, taxonomy, and habitat (terrestrial, spring, or wetland). We found a rough inverse correlation with elevation in modern shells from the Spring Range in southern Nevada. The delta 180 values of modern and fossil shells are also very different; modern values in this location are much higher than those from nearby late Pleistocene-age molluscs suggesting that the Pleistocene summers were variously colder and wetter than today or less evaporative (more humid). Assuming shell material directly reflects the 180 of the growing-season environment, comparison of modern and fossil shell delta 180 values can potentially identify changes in air-mass moisture sources and can help to define seasonal precipitation change through time. Comprehension and quantification of community and isotopic variability in modern gastropods is required to create probabilistic valid transfer functions with fossil materials. Valid inferences about past environmental conditions can then be established with known confidence limits.

STABLE ISOTOPIC ANALYSES IN PALEOCLIMATIC RECONSTRUCTION

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Keywords: *stable isotopes, paleoclimate, carbon 13, woodrat middens, ecophysiology*

ABSTRACT

Most traditional paleoclimatic proxy data have inherent time lags between climatic input and system response that constrain their use in accurate reconstruction of paleoclimate chronology, scaling of its variability, and the elucidation of the processes that determine its impact on the biotic and abiotic environment. With the exception of dendroclimatology, and studies of short-lived organisms and pollen recovered from annually varved lacustrine sediments, significant periods of time ranging from years, to centuries, to millennia may intervene between climate change and its first manifestation in paleoclimatic proxy data records. Reconstruction of past climate through changes in plant community composition derived from pollen sequences and plant remains from ancient woodrat middens, wet environments and dry caves all suffer from these lags. However, stable isotopic analyses can provide more immediate indication of biotic response to climate change.

Evidence of past physiological response of organisms to changes in effective precipitation as climate varies can be provided by analyses of the stable isotopic content of plant macrofossils from various contexts. These analyses consider variation in the stable isotopic (hydrogen, oxygen and carbon) content of plant tissues as it reflects 1) past global or local temperature through changes in meteoric (rainfall) water chemistry in the case of the first two isotopes, and 2) plant stress through changes in plant respiration/transpiration processes under differing water availability, and varying atmospheric CO_2 composition (which itself may actually be a net result of biotic response to climate change). Studies currently being conducted in the Intermountain West indicate both long- and short-term responses that when calibrated with modern analogue studies have the potential of revealing not only the timing of climate events, but their direction, magnitude and rapidity.

INTRODUCTION

Currently, study of paleobotanical data, pollen and plant macrofossils, provide an indication of the net effects of long-term increased effective precipitation. This is accomplished through the reconstruction of past plant communities and their comparison with the climate associated with their modern analogues. However, much current research is directed toward the evidence of past climates that may be derived from stable isotopes, in particular deuterium, oxygen 18, nitrogen 15 and carbon 13. Of particular utility in the investigation of plant remains from the past is carbon 13. The study of carbon 13 enrichment in plants may eventually provide more detailed information regarding the rapidity of climate change and the span of time during which excess rainfall may have been available for ground water recharge than any current technique.

STABLE CARBON ISOTOPE CLIMATIC SIGNALS IN PLANTS

Studies of respiration, chemical absorption of CO_2, and CO_2 diffusion as mechanisms of isotopic fractionation in plants led to the recognition of variability in the content of ^{13}C in plants (Craig 1953; Craig 1954; Park and Epstein 1960; Park and Epstein 1961; Kortschak et al. 1965; Hatch and Slack 1970). These and other studies demonstrated that significant variation in carbon isotopic fractionation in plants (i.e., differences between C_3, C_4 and CAM plants) occurred as a result of differences in plant metabolism. It was not until the early 1980s that study of the biochemical and physiological basis for these differences began in earnest (Farquhar et al. 1982). It was found that within these groups of plants (C_3, C_4 and CAM plants), within the same species, and even within the same organism differences in $\delta^{13}C$ occur that are conditioned by organismal response to environmental conditions.

In order for plants to grow they fix carbon that enters through leaf pores (stomata) as CO_2. Increased conductance of leaf stomata causes an increase in the partial pressure of CO_2. However, the resultant increase in the rate of CO_2 assimilation must be balanced with the increased rate of transpirational water loss (Farquhar et al. 1988). It is this need to balance these two factors that results in fractionation of stable isotopes of carbon in the plant.

Variation in isotopic fractionation of carbon in plants is due to several environmental parameters. Among these are: 1) habitat soil water content (Garten and Taylor 1992; Ehleringer et al. 1986; Ehleringer et al. 1987), 2) atmospheric humidity (Winter et al. 1982), 3) annual precipitation in dry localities (Garten and Taylor 1992), 4) exposure to light (Garten and Taylor 1992; Ehleringer et al. 1986; Farquhar et al. 1982; Francey et al. 1985), 5) atmospheric CO_2 stratification (Sternberg et al. 1989a; Sternberg et al. 1989b), or combinations of the latter two (Ducatti et al. 1991), 6) season of measurement (Garten and Taylor 1992), 7) differences in mean annual temperature (Morecroft and Woodward 1990), and, perhaps, 8) differences in stomatal density (Madsen 1973; O'Leary and Knecht 1981; Imai et al. 1984; Woodward 1987; Van der Water 1993).

Within the Great Basin the relative percentages of tree pollen as well as influx estimates of these species suggest, when they are available, that woodlands remained relatively open throughout the Pleistocene. Therefore, factors such as exposure to light and atmospheric CO_2 stratification through lack of canopy level mixing of air probably did not play a major role in $\delta^{13}C$ enrichment. Although occasional increases in atmospheric humidity may have effected $\delta^{13}C$ enrichment, drought and low temperature enrichment of $\delta^{13}C$, and perhaps changes in atmospheric CO_2 content were probably the major factors governing enrichment.

Given these constraints, my initial research suggests that the $\delta^{13}C$ data on whole plant material collected from woodrat middens in the Great Basin indicate that drought and low temperature have acted in concert at different time scales during the late Quaternary in effecting $\delta^{13}C$ enrichment in plant materials. A plot of $\delta^{13}C$ values of plant materials from strata of a single woodrat den in the Virginia Mountains of NW Nevada reveal enrichment trends contrary to those for the drought induced water stress expected from the reconstructed climatic trends of the last 30,000 years (Figure 1). In this case, a polynomial curve fit of the $\delta^{13}C$ values of plant materials, which are normally considered to be a measure of plant water use efficiency, show remarkable similarity to late Quaternary temperature variations suggesting that temperature may be a strong long-term influence. A similar conclusion can be drawn

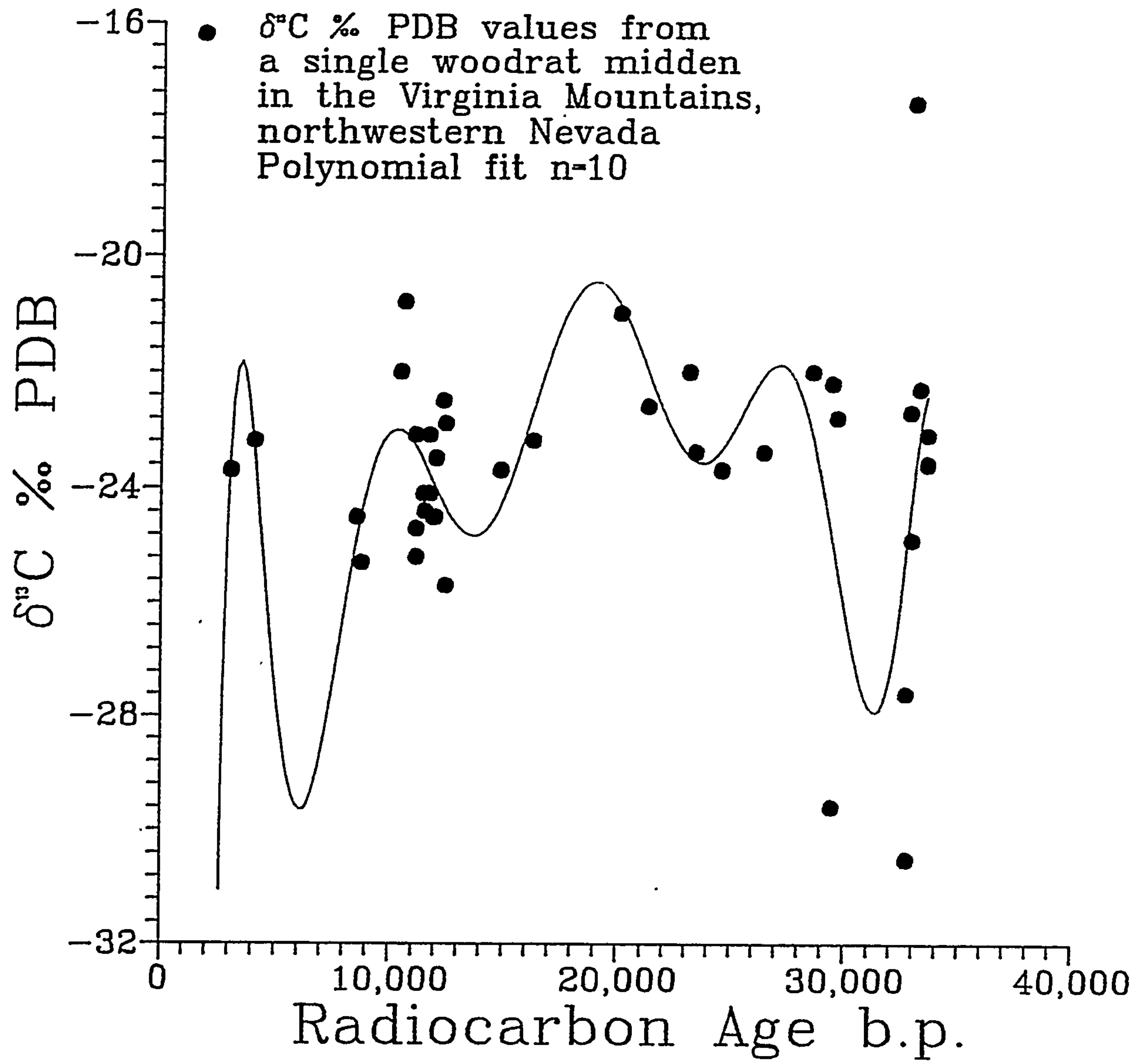

Figure 1. Plot of $\delta^{13}C$ values on plant materials from strata of a single woodrat den in the Virginia Mountains of NW Nevada. The $\delta^{13}C$ values of plant materials are normally considered to be a measure of plant water use efficiency. However, a polynomial curve fit and its similarity to late Quaternary temperature variations suggest that temperature may be a strong influence over the long-term.

from a best fit curve plotted against the $\delta^{13}C$ values of materials obtained from woodrat midden strata sampled regionally around the pluvial Lake Lahontan basin (Figure 2).

Therefore, long stable isotopic records from a single locality mirror the massed data from an entire region. Both reflect the long-term effect of temperature, whereas short-term outliers (the apparent noise) probably reflect increased water use efficiency as a result of "real" droughts. The long-term regional temperature pattern can be extended with a comparison of the $\delta^{13}C$ values from the Virginia Mountain midden in NW Nevada and the values obtained by Siegel (1983) from North Snake Range

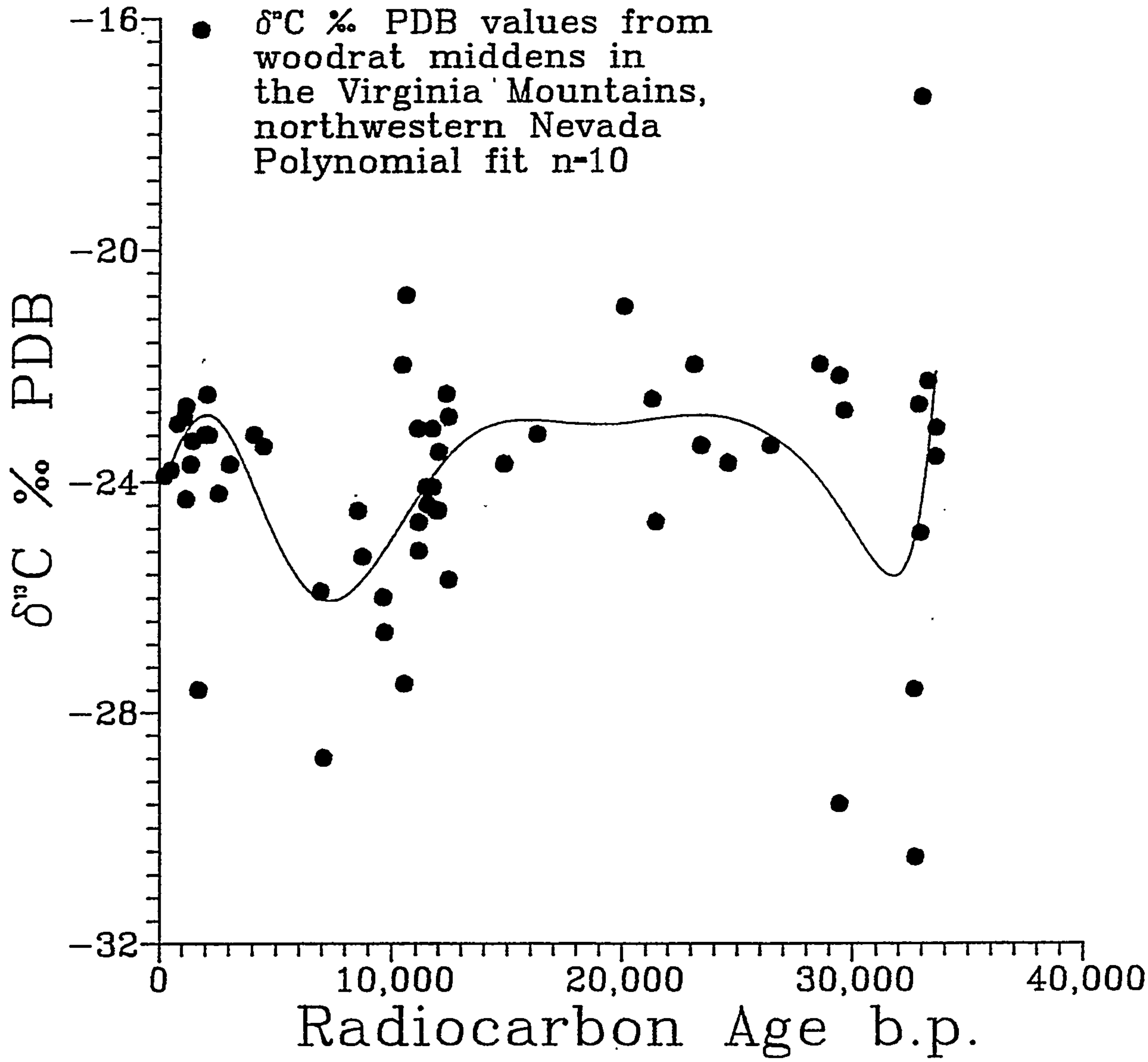

Figure 2. When a best fit curve is plotted against the $\delta^{13}C$ values of materials obtained from woodrat midden strata around the pluvial Lake Lahontan basin the result looks much as did that from the single nest from the Virginia Mountains (Figure 1). Therefore, long stable isotopic records from a single locality mirror the massed data from an entire region. Both reflect the long-term effect of temperature, whereas short-term outliers probably reflect increased water use efficiency as a result of droughts.

middens in eastern Nevada (Figure 3). This similarity can be extended to southern Nevada as well (Figure 4).

Well-dated fossil pollen records from continuous lake sediment cores are being analyzed to corroborate the conclusions drawn from both the stable isotope and midden plant macrofossil records. Pollen records are the only certain way in which the direction, magnitude and duration of vegetation changes can be verified. Clear corroboration of the conclusion that long-term $\delta^{13}C$ enrichment is driven by temperature is provided by the effective

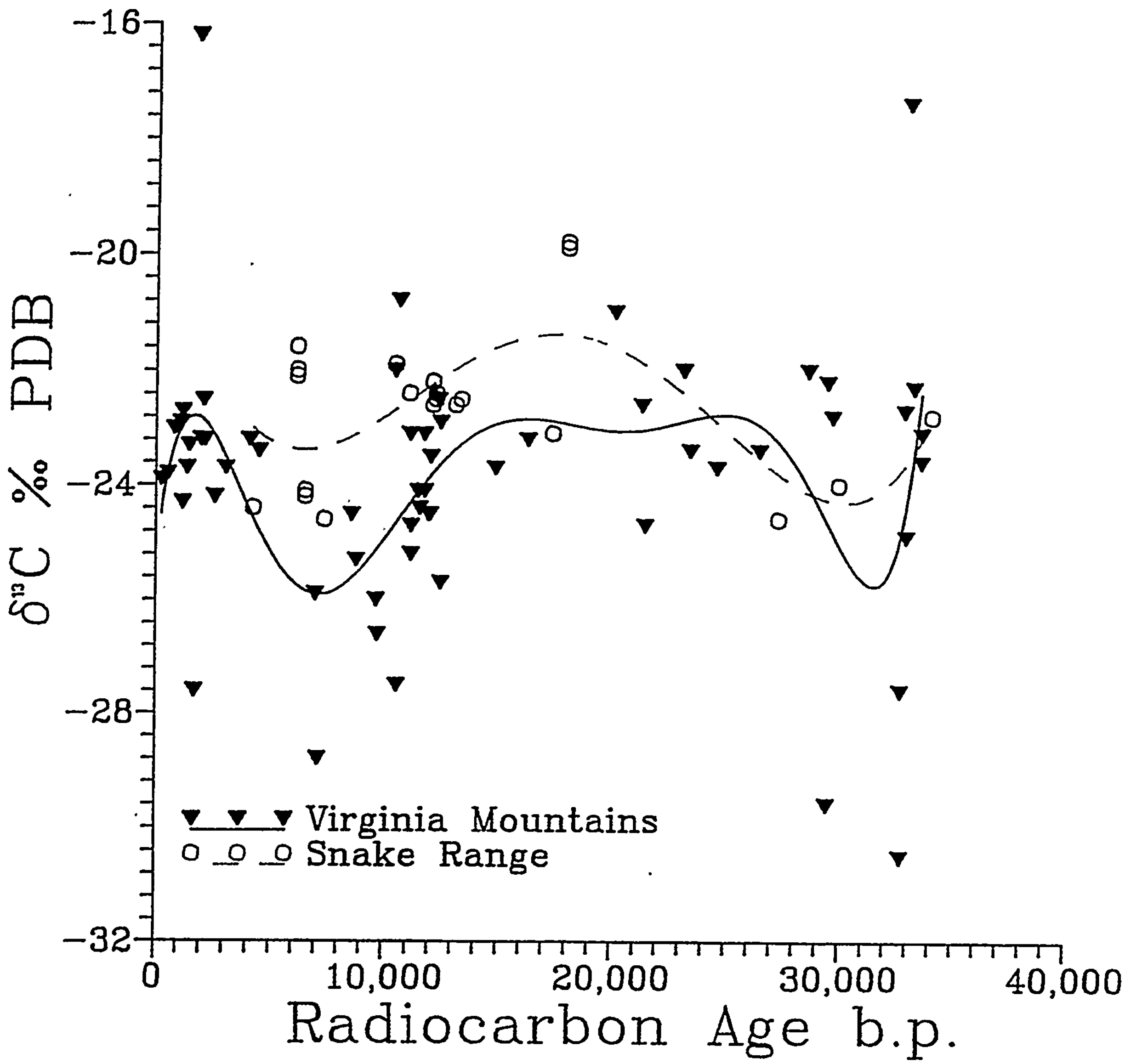

Figure 3. The long-term regional temperature pattern is also revealed in a comparison in the figure above of my $\delta^{13}C$ values from the Virginia Mountains midden in NW Nevada (triangles with the straight line) and the values obtained by Siegel (1983) from North Snake Range middens in eastern Nevada (squares with the dashed line).

rainfall ratio generated by the pollen record from Lower Pahranagat Lake over the last 2,000 years (Figure 5). Increased proportions of pine and juniper pollen versus saltbush pollen types reflect vegetation community response to greater effective precipitation. In this case, increased ratio values correspond to the terminal "Neoglacial," the late Roman period and the "Little Ice Age," all well recognized periods of cooler climate with effectively greater precipitation (Figure 5).

Therefore, long-term trends in $\delta^{13}C$ when compared with the vegetation record in the Great Basin, reveal that periods of wetter-climate vegetation correspond to more positive $\delta^{13}C$ values or enrichment driven by temperature. This appears to happen despite the

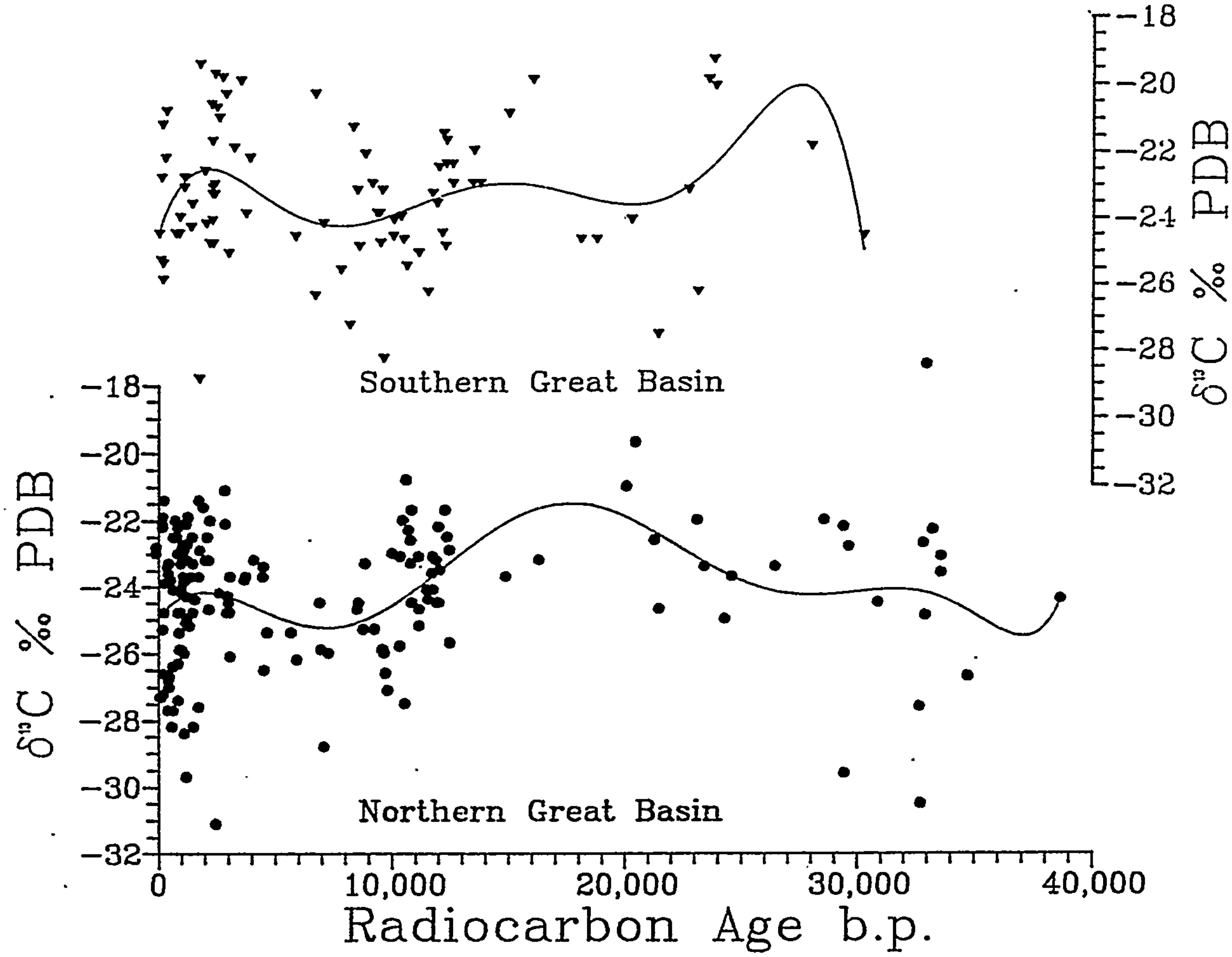

Figure 4. The pattern that appears in Figure 3 is also apparent when $\delta^{13}C$ values from northern Nevada are compared with those from southern Nevada.

presence of greater moisture during these periods. Increased water use efficiency may, in this case, be triggered by "drought" as caused by the tie-up of water as ice in the ground during the growing season (shortened growing seasons may be crucial) (Morecroft and Woodward 1990).

Increased ^{13}C enrichment could also occur during periods when cold spring temperatures would force the growing season later into the year, well after most of the annual rainfall had occurred. However, if this were the case the shift from dry to wet plant community species should not occur. If anything, a shift in the opposite direction in plant community species composition would be expected.

Although most short-term trends seem to reflect "real drought" resulting from decreased rainfall (Ehleringer 1988), there are short-term fluctuations that are not so easily explained.

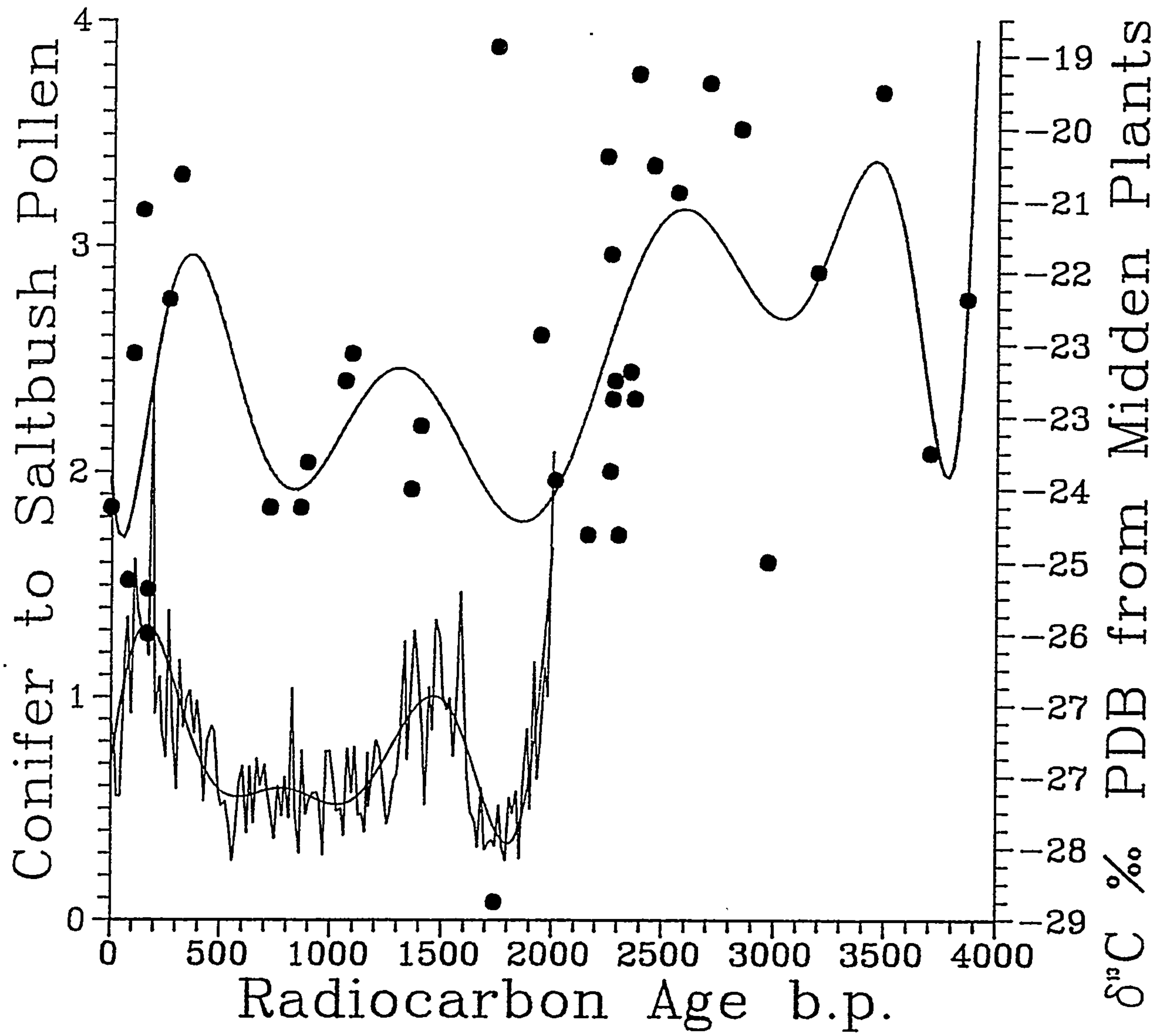

Figure 5. Comparison of the $\delta^{13}C$ values for the last 2,000 years in the Yucca Mountain area with the Conifer to Saltbush Pollen ratio from Lower Pahranagat Lake. It is clear that periods of cooler temperature with increased effective, winter-dominated rainfall correspond to increased $\delta^{13}C$ enrichment.

The resolution of these contradictions may lie in the competition of individual plants for water within the plant community in a desert environment.

Plants adapted to the semi-arid climates of the Great Basin have a tremendous capacity to respond to increased water availability with dramatic increases in biomass production, e.g., the biomass increase of plants to the significantly greater rainfall of the early 1980s. If more water is available than can be assimilated by plants through increased size, new plants will grow and fill the spaces between the older plants. If still more water is available, a shift to new plant species occurs resulting in the community composition changes that typify the last 40,000 years of the vegetation record recovered from ancient woodrat middens. Under these new conditions even more water can be assimilated. However, because these species have to migrate into the area, a lag time occurs between the time that climate change actually occurs and the establishment of the new plant community. Eventually, however, the new plant community will assemble, and through size and spacing adjustments plants will assimilate the excess water.

When development of the new plant community is complete competition for available water again becomes acute. However, at this point competition for water occurs at a different level of equilibrium reflecting the greater availability of water and the greater requirements of the new community. Therefore, although pollen and plant macrofossil materials indicate that a wetter climate vegetation is now predominant, plant water stress induced by the competition for water may become the driver of $\delta^{13}C$ enrichment. This is especially true of plant communities in semi-arid regions were small changes in rainfall can dramatically affect plant community composition. Under the extreme water stress conditions that are quite common in these regions plant communities, especially the ones at the mesic end of the scale, become susceptible to disturbance phenomena, such as disease, insect infestation and fire. If conditions of water stress persist the more mesic plant communities will eventually be destroyed and be replaced with shrubs and forbs that are less water demanding and therefore less stressed by the competition for water. These plants will have less enriched values of $\delta^{13}C$. In most cases during the Holocene these species have been present within the plant community in the understory vegetation.

During the transition from arid-plant community to a completely developed wetter-climate community, increasing water use efficiency (as reflected by $\delta^{13}C$ enrichment) reveals the decreasing availability of excess water as it is utilized by plants. This excess water is what is available for both runoff and recharge during wet periods. It is the competition for water by plants during the transitions from drier to wetter plant communities which may account for some of the unexplained variation that is clear in the $\delta^{13}C$ value records from the northern Great Basin during the last 4,000 years (Figure 6). These transitional periods should be studied to determine the amount of water that may be available for movement through the aquifers during periods of extreme precipitation.

The sequence of events during a transition from drier to wetter climate vegetation would be as follows. Initially—even before plant community composition would change—both increased pollen production (more pollen per square centimeter per year) and a sudden brief decrease in the $\delta^{13}C$ content of plant materials sequestered in contemporaneous woodrat middens or tree-rings would signal the onset of wetter climate. As the plant community responds with increased biomass production and eventual introduction of new species, the water availability would decrease and relative $\delta^{13}C$ enrichment would increase as plants attempted to conserve the increasingly sparser resource. Maximum relative enrichment values in the members of the plant community should occur when the new community has maximized its use of the available water. At this point little water will be available for recharge.

Obviously, there will be short-term fluctuations in response to wet and dry years, but the long-term indication in the stable isotopic record would reflect the impact on water availability caused by acute competition of the "climaxed" vegetation for available water. The $\delta^{13}C$ values of the "climaxed" vegetation would still be less positive than those that would occur during a severe drought. However, on the other hand, they would be more positive than those values for the same plant community while water was still in excess. Comparison of the $\delta^{13}C$ values from shrub macrofossils with the $\delta^{13}C$ values from tree macrofossils in the same midden strata indicate that $\delta^{13}C$ values from tree materials are

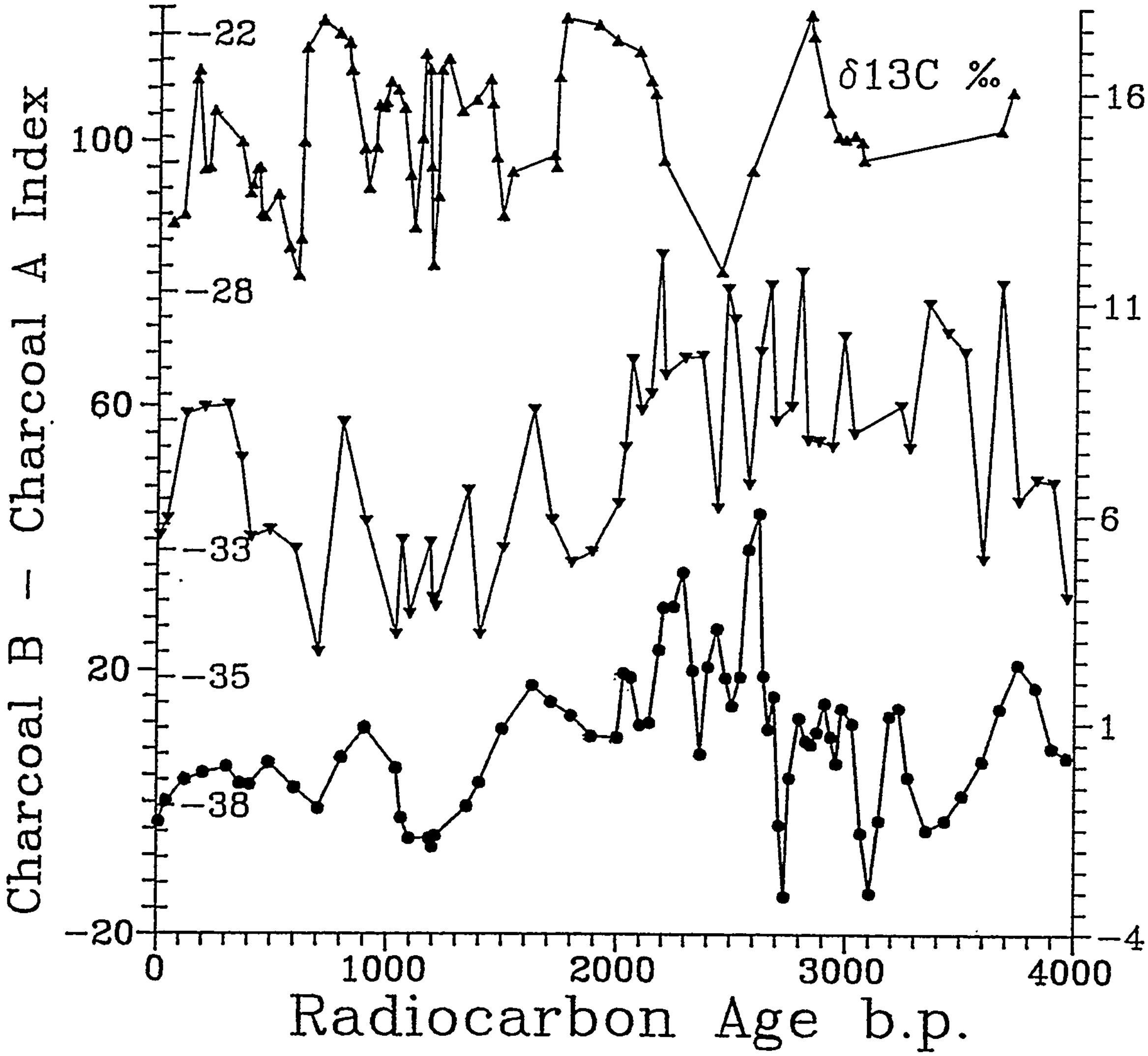

Figure 6. Comparison of (from bottom to top) ratio of large to small charcoal from the Diamond Pond record, ratio of juniper to grass and $\delta^{13}C$ values from the northern Great Basin. In this figure the ratio of juniper to grass pollen from Diamond Pond indicates periods of wetter, winter dominated climate (juniper dominance), many of the short-term fluctuations in $\delta^{13}C$ indicate periods of reduced rainfall, i.e, real "drought," and long-term variations in $\delta^{13}C$ because of its match to reconstructed global temperature for the last 30,000 years or so probably reflect the cold temperatures of the "Neoglacial," post 1 ka period, and the "Little Ice Age." Finally, the charcoal values indicate the increase in regional fires once juniper woodland became well established and through stress susceptible to "drought" period fires. A similar pattern occurs in southern Nevada with a comparison of the Lower Pahranagat Lake pollen and charcoal records and the $\delta^{13}C$ values obtained from local middens (Wigand unpublished data).

enriched relative to shrub materials (Figure 7). This suggests that shrubs in the same community are less stressed than are trees at the same time. This is logical because most of the shrub species are those typically found in drier vegetation communities and would be more drought tolerant than would the more mesic community tree species. The relationship of climate, productivity and competition for resources reflected in these data mirror that already clearly revealed in dendroclimatology (Fritts 1976).

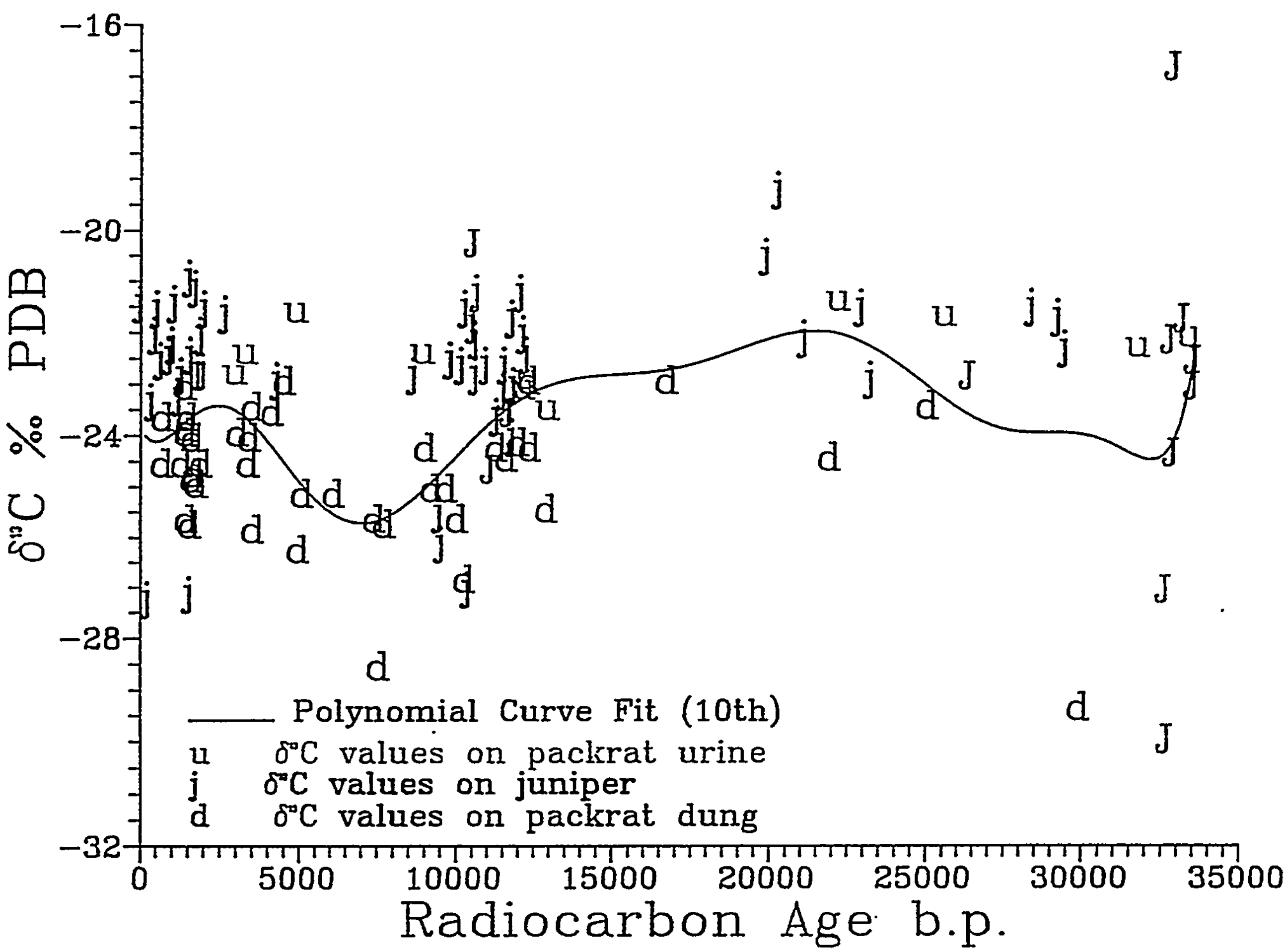

Figure 7. When $\delta^{13}C$ values from middens throughout the pluvial Lake Lahontan basin are plotted by material that was analyzed, differences are obvious. These may simply reflect sampling bias (i.e., uneven chronometric distribution of the samples). In general, $\delta^{13}C$ values on urine had the greatest enrichment, with $\delta^{13}C$ values on juniper less enriched and $\delta^{13}C$ values on dung the least. The $\delta^{13}C$ values on dung may reflect the admixture of more drought and cold tolerant shrub species with juniper in the fecal pellet.

CONCLUSIONS

Late Holocene changes in plant community composition in both northern and southern Nevada reflect periods of effectively moister climate. These intervals are generally coincident with regrowth of Great Basin marshes and increased spring discharge, i.e., ~ 3.6 ka, from 2.3 to 1.9 ka, ~ 1.0 ka and ~ .35 ka. Variations in the proportions of stable isotopes of carbon in radiocarbon dated plant materials from fossil middens apparently provide a means of gauging the rapidity of vegetation response to increased water availability at the organismal level. In addition, such variations provide a means of determining the duration and amount of water available for recharge during the transitions from one vegetation type to another. The amount of water available for recharge during the transition from drier to wetter plant communities in general should approximate the difference in rainfall between the more mesic and more xeric vegetation communities that were replaced. The span of time between the first indication of changed climate and the point when water use efficiency is greatest ($\delta^{13}C$ values are greatest) in the new plant community is the period when excess water would be available for groundwater recharge or surface discharge. The decreasing amount of water available through time is probably inversely proportional to the increase in water use efficiency as reflected in the $\delta^{13}C$ values of the plant record. These assumptions can be imperially tested with modern analog studies. If these prove correct their application to analyses of ancient midden records from the late Quaternary would lead to new understandings regarding the relationship of plants to their environment.

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Session II: Paleoclimatic Data—Holocene

A DETAILED 2,000-YEAR LATE HOLOCENE POLLEN RECORD FROM LOWER PAHRANAGAT LAKE, SOUTHERN NEVADA, USA

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Keywords: *paleobotany, paleoclimate, Great Basin, late Holocene, southern Nevada*

ABSTRACT

Preliminary analysis of 128 pollen samples and seven radiocarbon dates from a 5-meter long, 10-cm diameter sediment core retrieved from Lower Pahranagat Lake (elevation - 975 m), Lincoln County, Nevada, gives us a rare, continuous, record of vegetation change at an interval of every 14 years over the last 2,000 years. During this period increasing *Pinus* (pine) pollen values with respect to *Juniperus* (juniper) pollen values reflect the increasing dominance of pinyon in southern Nevada woodlands during the last 2,000 years. Today *Pinus* pollen values indicate that pinyon pine is more frequent in the southern Great Basin since the end of the Neoglacial 2,000 years ago. During the same time frame, a general decrease in Poaceae (grass) pollen values with respect to *Artemisia* (sagebrush) pollen values reflect the general trend of increasing dominance of steppe and desert scrub species with respect to grasses. Variations in these two species reflect not only the generally more xeric nature of climate during the last 2,000 years, but also periods of summer shifted rainfall ~ 1,500 years ago that encouraged both a period of grass and pinyon expansion.

The ratio of aquatic to littoral pollen types indicates generally deeper water conditions 2 to 1 ka and more variable, but predominately more marshy, conditions at the site during most of the last 1 ka. Investigation of ostracodes from the same record being conducted by Dr. R. Forester at the USGS corroborate the pollen record by evidencing shifts between open and closed hydrologic systems including lake, marsh and even stream habitats. Analysis of an additional 10 meters of core recovered in the summer of 1994 with a basal date of 5.6 ka promises to provide the best record of middle through late Holocene vegetation and climate history for southern Nevada.

INTRODUCTION

The prospect that Yucca Mountain may become a repository for high-level radionuclides with especially long half-lives means that the intended waste containment area must be well beyond the reach of the hydrologic system. Assessment of site suitability and design appropriateness requires clear understandings of the directions, magnitudes and rapidity of climate changes and their impact upon ground water regimes. Because historic climate records indicate very little regarding the possible range of climate even during the last 500 years, full understanding of the possible impacts of future climate change requires knowledge not only of the range of modern climates, but also of past climates. In particular, patterns of past climate variation must be explored in order to reveal the possible range of climate that may reasonably be expected during the next 10,000 years or so when these materials have decayed sufficiently to render them harmless. Although studies of orbital mechanics, provide speculative notions of future climatic trends, they cannot be used to predict how these trends will manifest themselves in the immediate vicinity of Yucca Mountain, or even, at present, in the Intermountain West. In order to address these concerns, conditions under which extremes of wetter climate have occurred during the late Quaternary (the last 200,000 years) must be considered and used as a guide to the likely range of future climate variation.

One method for estimating the past climate of a region is to examine its vegetation history. Although other proxy data sets, e.g., diatom and ostracode, can be used to reconstruct detailed lacustrine, riparian and spring discharge histories and relate them to regional precipitation, reconstructed terrestrial vegetation provides additional information crucial for determining the conditions under which past ground water recharge occurred. Knowledge of the kind, extent and density of past vegetation communities aids in assessing the impact of evapotranspiration and plant uptake on the amount of water that may be available for recharge.

Typically, in the arid West reconstructed climate history has been based upon analyses of pollen from stratified deposits in lakes, marshes and alluvium, and upon plant remains preserved in ancient woodrat nests (middens). Paleobotanical data are used to reconstruct changes in plant community composition which reflect general trends in changing precipitation and temperature (Mehringer 1985; Mehringer 1986; Betancourt et al. 1990). Whereas woodrat midden studies concentrate on the appearance and disappearance of specific indicator species that characterized changing plant communities, analyses of pollen records result in the reconstruction of long-term, relatively continuous, shifts in the gross composition of plant communities. In part, this focus has been dictated by the techniques that have been available to investigators, and by issues of time and money.

During the last two decades techniques, more amenable to the investigation of past plant response to climate change at the organismal level, have been inaugurated in paleobotanical analyses to extend our knowledge of plant community history, and to reveal answers regarding differences and/or similarities in the physiological response of plants during the Holocene and the Pleistocene (Long et al. 1990; Van de Water 1993; Mehringer and Wigand 1990; Wigand and Rose 1990). Integration of past and ongoing research on vegetation histories derived from Great Basin pollen and woodrat midden records reveal large scale changes in temperature and precipitation both in northern and southern Nevada.

POLLEN AND PLANT MACROFOSSIL RECORDS

Currently researched pollen records in southern Nevada include: our own from the Oasis Valley northeast of Beatty, Nevada, and Lower Pahranagat Lake south of Alamo, Nevada, and those of P. J. Mehringer from Tule Springs in the Las Vegas Valley and from Ash Meadows west of the Spring Range (Figure 1). These form the basis of relatively continuous late Holocene and intermittent Pleistocene reconstructions of vegetation history around the Nevada Test Site (Wigand and Rose 1990; Mehringer 1967; Mehringer and Warren 1976). Regional terrestrial pollen and the pollen of local littoral and aquatic plants record periods of both local and regional vegetation change and local water table fluctuation in response to climate change during the last 2,000 to 6,000 years. Fluctuations in juniper and pine pollen in the well-preserved record from Lower Pahranagat Lake reflect variation in winter precipitation, and in particular its impact on intermediate elevation forests. Juniper pollen values vary between 5 and 22 percent (Figure 2). These values reflect major changes in distribution, density, and

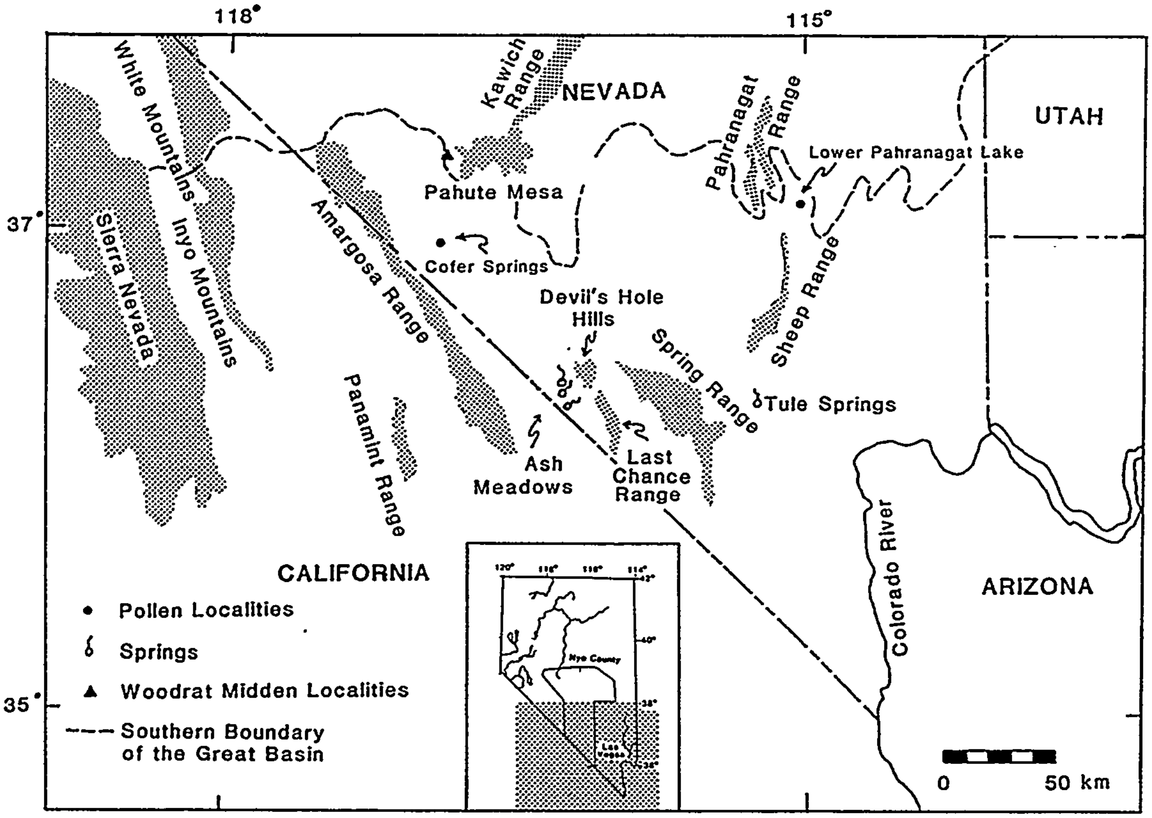

Figure 1. Map of southern Nevada indicating some of the locations mentioned in the text.

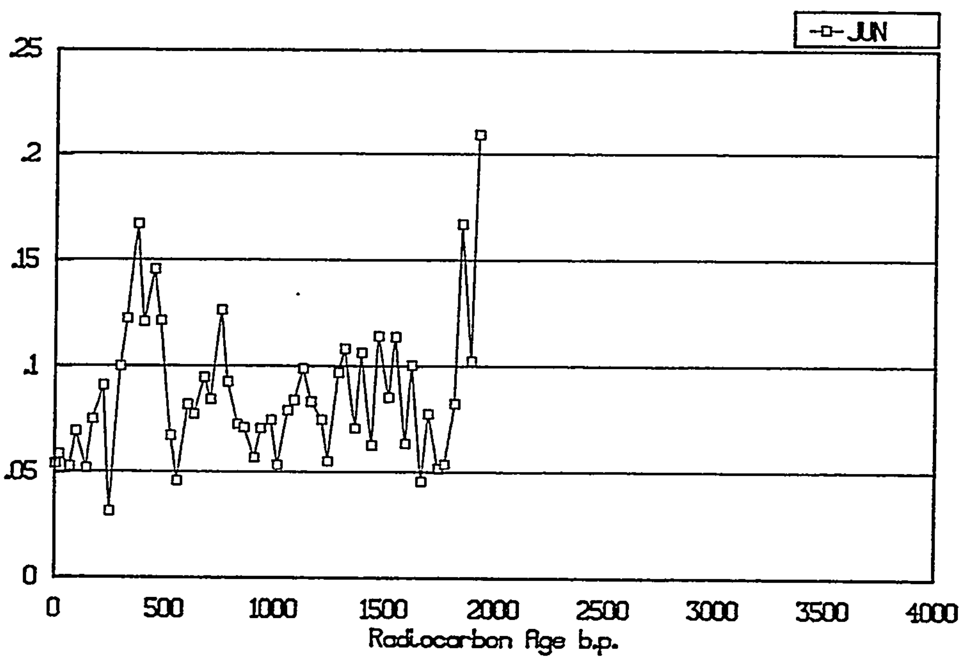

Figure 2. Index of juniper pollen values from the Lower Pahranagat Lake record plotted by age for the last 2,000 years indicating periods of winter dominated rainfall.

productivity of juniper on the landscape and, in fact, suggest that juniper may have grown significantly nearer Lower Pahranagat Lake until around 2 ka (Wigand and Rose 1990). This would indicate a drop in lower tree-line of one to two hundred meters. Woodrat midden data from the Sheep Range south of the lake suggest that there may have been as much as a 200 m depression in lower tree-line centered between 2 and 4 ka (Spaulding 1981; Spaulding 1985). Reconstructed deposition rates of the high resolution Lower Pahranagat Lake record (a sample every 14 years for the last 2,000 years) suggest that at times the transition to higher juniper pollen values may have taken only a few decades. The local increase in effective precipitation necessary to accomplish this change, based upon the difference in the minimal annual rainfall requirements between Sagebrush (Mozingo 1987) and Utah Juniper (Leonard et al. 1987), must have been at least 10 to 20 mm per year and could have been as much as 70 mm per year. Reduced evaporation rates due to reduced mean annual temperature may have played a significant role in increasing effective precipitation.

In addition to the fluctuation in juniper pollen values, there is an overall increase in pine pollen values over the last 2,000 years (Figure 3). Increases in pine also highlight a period ~ 1.5 ka of regional pinyon expansion that is marked by a corresponding increase in grass pollen values (Figure 4). This may evidence a period of summer shifted rainfall. Juniper responds little during this period. Shrub steppe species, in particular sagebrush, did poorly during this period (Figure 5). In general, however, sagebrush has been on the increase during the last 2,000 years.

At Lower Pahranagat Lake, two additional increases in juniper pollen, indicating greater effective precipitation resulting from increased winter precipitation and reduced evaporation rates, occur ~ .7 ka and ~ . 3 ka (Figure 2). Although these are not as significant as the one evidenced ending about 2 ka they are mirrored by the pollen record from Cofer Spring north of Beatty, Nevada (Wigand and Rose 1990) and at Warm Sulfur Springs in the Panamint Valley (Smiley and Mehringer no date). Further evidence for these increased precipitation events is recorded in the sequence of dune and peat layers from Ash Meadows (Mehringer and Warren 1976). Although complicated by dune movement and the possibility of neo-tectonic activity, the formation of these peat strata reflect increased discharge of the major springs in Ash Meadows during four periods of peat formation spanning the past 5.3 ka: 1) between 5.3 and 4.45 ka; 2) between 4 and 3.6 ka; 3) about 3 ka; and 4) about .4 ka. Of these, the last can be correlated with the records obtained from Lower Pahranagat Lake and Cofer Spring. At Warm Sulphur Springs in the Panamint Valley, California sedge seeds from a peat dated to 3,400±500 b.p. and from one dated to ~ .23 ka record two episodes of peat growth that reflect periods of increased effective precipitation from other southern Nevada records (Smiley and Mehringer no date). Additional corroboration of these events is provided by the record from Little Lake in the Owens Valley south of Bishop, California. Here periods of greater effective precipitation during the past 4,000 years roughly span the periods from about 2.8 to 2 ka, from 1.9 to 1.5 ka, from ~ 1.15 to .7 ka, and since ~ .35 ka (Mehringer and Sheppard 1978). Unfortunately, old ground water carbon contamination of datable materials from those pollen cores precluded a formulation of good chronology with the radiocarbon techniques of the time (today AMS dating can be used to obtain dates on small samples that have terrestrial origin in such sediments and are therefore unaffected by ground water contamination). It is clear, however, that there have been at least four late Holocene periods of regionally increased effective precipitation during the last 4,000 years in the southern Great Basin.

Just how extensive these events were can be resolved through a comparison with the record from Diamond Pond in the Harney Basin of south-central Oregon in the northern Great Basin (Wigand 1987). Although over

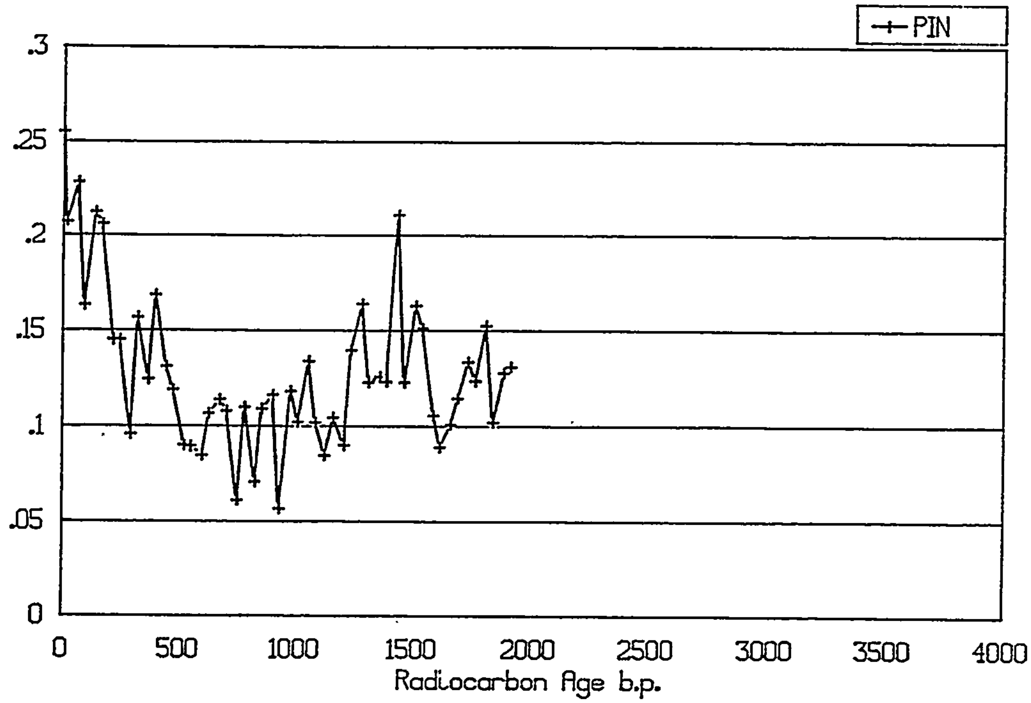

Figure 3. Index of pine (primarily pinyon) pollen values from the Lower Pahranagat Lake record plotted by age for the last 2,000 years indicating the two major periods of its expansion.

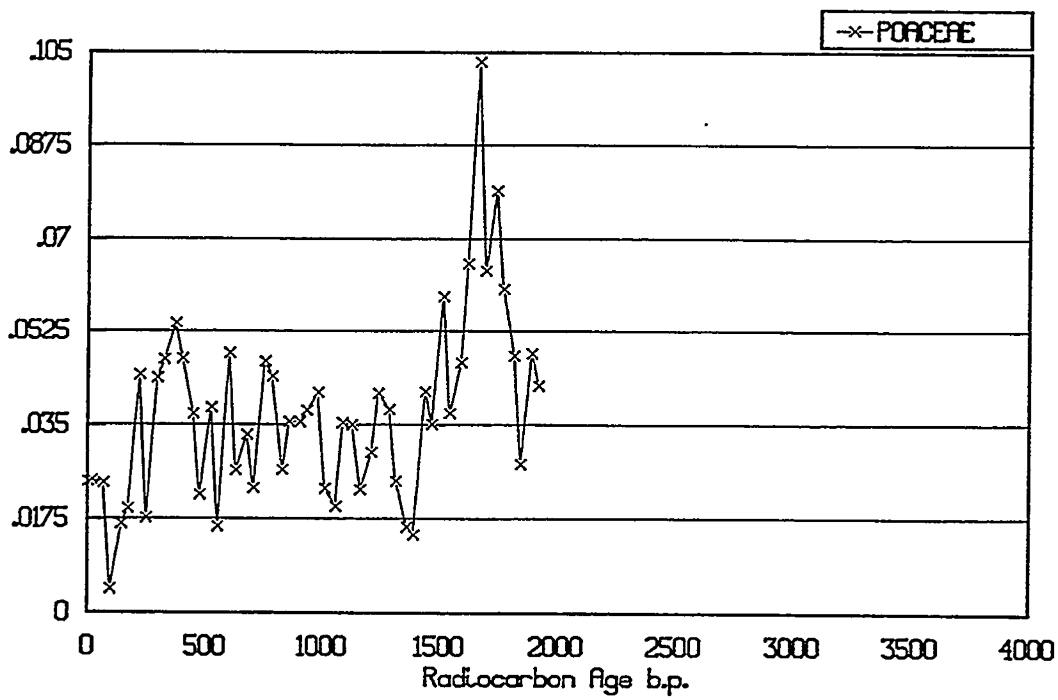

Figure 4. Index of Poaceae (grass) pollen values from the Lower Pahranagat Lake record plotted by age for the last 2,000 years indicating the gradual decrease in its abundance.

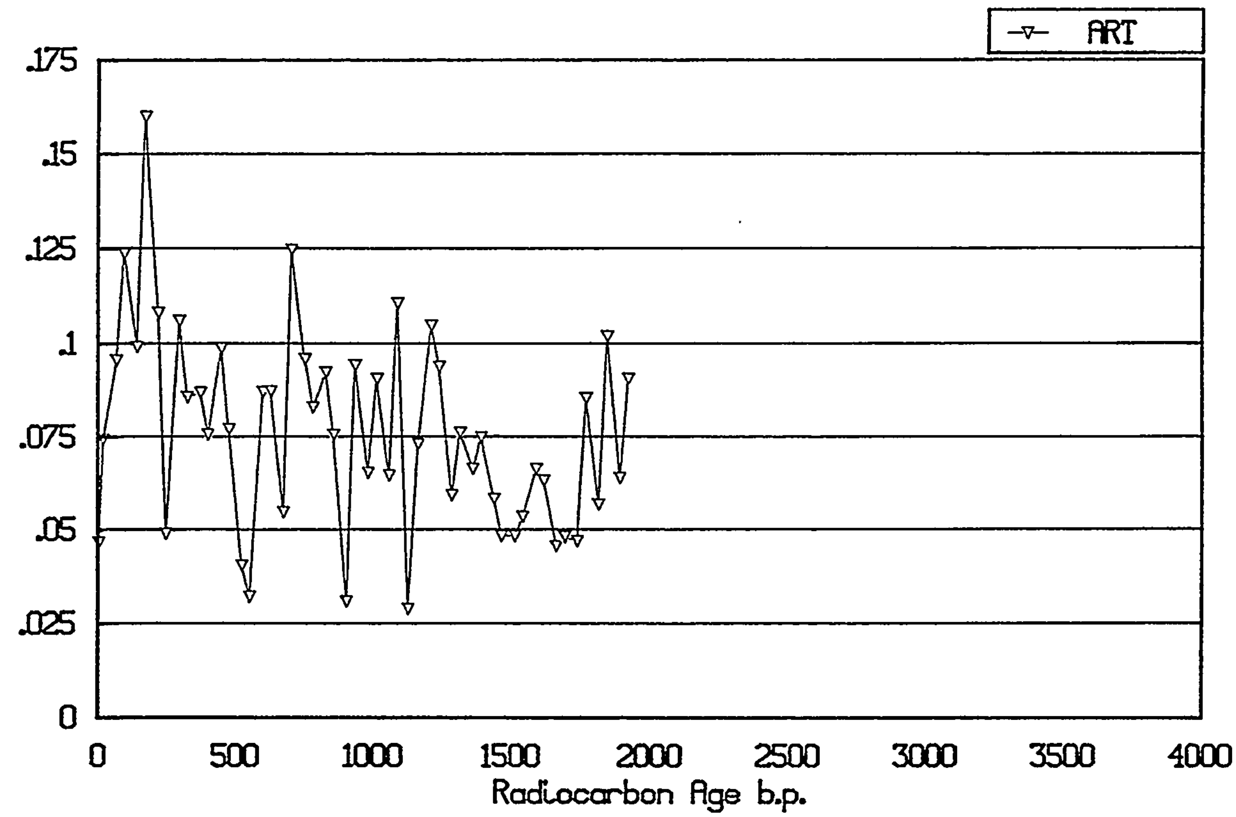

Figure 5. Index of Artemisia *(sagebrush) pollen values from the Lower Pahranagat Lake record plotted by age for the last 2,000 years indicating the gradual increase in its abundance.*

1300 kilometers further north, it is well dated and the correspondence of wet and dry periods with those identified in southern Nevada is surprising. Using the ratio of aquatic to littoral plant macrofossils at Diamond Pond as an accurate indication of water table fluctuations and regionally increased effective precipitation, the timing of wet periods are as follows:
1) between ~ 3.75 and 3.45 ka, 2) ~ 2.8 to 2.6 ka, 3) from 2.35 to 2.05 ka, 4) from 1 to .8 ka, and 5) from .3 to .15 ka (Figure 6). Except for the period ~ 2.8 to 2.6 ka these events correspond closely with those of southern Nevada. However, following the 5.3 ka amelioration of middle Holocene drought conditions—recorded as far north as Wildcat Lake in the Columbia Plateau of Washington State (Blinman et al. 1979) and as far south as Ash Meadows, Nevada (Mehringer and Warren 1976)—the most significant event in all these records is the one centered ~ 3.6 ka. This appears to be the interval of greatest "Neoglacial" effective precipitation increase. This period corresponds to extensive marsh expansion in the northern Great Basin as evidenced in the archaeological records of caves and marsh margin sites (Aikens 1993).

Additional support for these conclusions are evident in the sudden increase in abundance of woodrat middens during these periods of wetter climate both in the northern Great Basin (Mehringer and Wigand 1990; Wigand and Nowak 1992) and southern Nevada (Wigand 1990), and in greater effective precipitation recorded in the tree-ring records from the White Mountains at 3.3 ka, between 2.3 and 1.9 ka, ~ .8 ka and during the last 200 years (LaMarche 1974). However, apparently

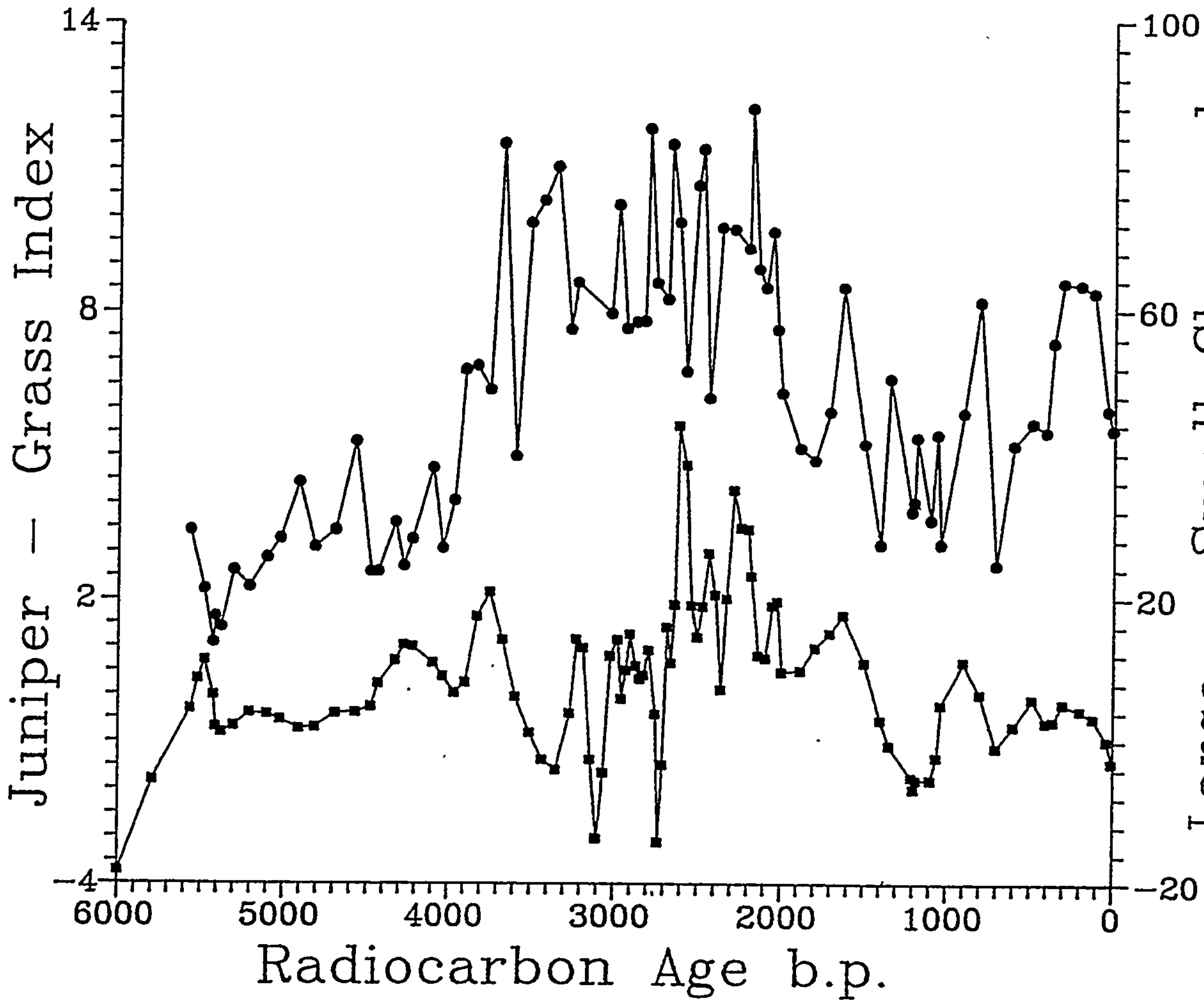

Figure 6. Juniper to grass pollen index (circles with the straight lines) from Diamond Pond, south-central Oregon for the last 6,000 years. Periods of winter dominated rainfall are clear between 2 and 4 ka, ~ 1 ka and about .3 ka. (Large to small charcoal is a square with a straight line.)

contradictory evidence was indicated in the data derived from the $\delta^{13}C$ record obtained from woodrat midden plant macrofossils of these more mesic periods.

CONCLUSIONS

In considerations of high-level nuclear waste storage Pleistocene conditions are usually offered as the most extreme that might affect the integrity of a waste storage facility. Holocene conditions, especially those of the last few thousand years are mistakenly assumed to be quite stable. Pollen data combined with other paleoclimatic proxy data sets from southern Nevada indicate that considerably wetter, as well as drier conditions have occurred resulting in dramatic responses in vegetation communities. Variations in not only woodlands, but also shrub communities and the grasses that grow among them provide evidence of significantly wetter periods of climate that, in most cases, are regionally expressed.

Variations in the duration and the rapidity of the onset and demise of these shifts is clear from the pollen record. Sample spacing of a sample of 14 years makes it clear that some of these shifts occur in less than a decade. Shifts to wetter climate of such speed with local vegetation initially unable to respond to the increase in precipitation would result in considerable excess water that would be available both for runoff and recharge. Finally, although the Holocene as a whole has been drier than the Pleistocene, higher resolution sampling of paleoclimatic proxy records indicate that there have been events of short duration that have approached the extremes recorded during the Pleistocene. The important difference is duration. If these Holocene events had continued over several hundred years they might well have initiated responses in regional vegetation that matched those of the Pleistocene.

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GREAT BASIN SEMI-ARID WOODLAND DYNAMICS DURING THE LATE QUATERNARY

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Keywords: *woodland history, paleoclimate, juniper, piñon, fire history*

ABSTRACT

Semi-arid woodlands have dominated the middle elevations of Great Basin mountain ranges during the Holocene where subalpine woodlands prevailed during the Pleistocene. Integration of paleobotanical proxy data reveals Great Basin semi-arid woodland dynamics in great detail for the last 4 ka and more coarsely for the last 35 ka. Ancient woodrat middens, and in a few cases pollen records document late Pleistocene and early Holocene woodland history. These indicate lowered elevational distribution of subalpine woodland species at times by as much 1,000 meters. After a middle Holocene retrenchment at elevations in excess of 500 meters above where they are found today, semi-arid woodlands began a downward expansion. Late Holocene pollen records from Cofer Springs, northeast of Beatty, Nevada, from Lower Pahranagat Lake, south of Alamo, Nevada, from Little Valley, southwest of Reno, Nevada, and from Diamond Pond in the Harney Basin of south-central Oregon indicate that juniper-dominated semi-arid woodland reached its late Holocene maximum areal extent during the Neoglacial (2 to 4 ka). These records, together with those from Lead Lake in the Carson Sink near Reno, Nevada, and McCoy Flat along Pine Creek near Eagle Lake, northern California, indicate contracting semi-arid woodland (primarily a regional decline in juniper) after the Neoglacial about 1.9 ka. Desert shrub community expansion coupled with increased precariousness of wetland areas in the southern Great Basin between 1.9 and 1.5 ka coincide with shrinking wetlands in the west-central and northern Great Basin. Coincident greater grass abundance in northern Great Basin sagebrush steppe, reaching its maximum between 1.5 and 1.2 ka, corresponds to dramatic increases in bison remains in the archaeological sites of the northern Intermontañe West (northern Great Basin, the Snake River Plain and the Plateau of eastern Washington). Pollen and woodrat midden records in the mountain ranges just east of the Sierra Nevada near Lake Tahoe indicate that this drought ended about 1.5 ka. Succeeding ameliorating conditions resulted in the sudden northward and downward expansion of piñon into areas that had been dominated by juniper during the Neoglacial. Both grass and piñon increases seem to reflect a shift toward summer season rainfall. However, piñon expansion may also reflect responses to less harsh winter conditions and longer growing seasons. Maximum areal extent of piñon dominated semi-arid woodland in west-central Nevada was centered at 1.2 ka. This followed by 100 years the shift in dominance from juniper to piñon in southern Nevada semi-arid woodlands. These two changes signaled the end of post-Neoglacial drought conditions in central and southern Nevada. Great Basin woodlands suffered from renewed severe droughts between .5 to .6 ka. Effectively

wetter conditions during the "Little Ice Age" resulted in re-expansion of semi-arid woodland throughout the Great Basin ~ .35 ka modified prehistoric. Activities related to European settlement in the Great Basin have modified prehistoric factors or imposed new ones that are affecting woodland response to climate.

INTRODUCTION

Late Quaternary climate is characterized by extremes of temperature and precipitation (Antevs 1938; Davis 1982; Mehringer 1986). In addition, recent paleoclimatic analyses indicate that the season of maximum precipitation and seasonal temperature extremes have also varied through time and across space in the West (Davis 1982; Thompson and Hattori 1983; Wigand and Nowak 1992; Wigand et al. 1994; Van Devender et al. 1987). These changes must be considered in evaluating the suitability of any nuclear waste storage facility in the near or distant future. Increased precipitation in the future could initiate the movement of radionuclides into the ground water. Impacts of past periods of wetter climate can be evaluated to assess this possibility. Currently, changes in plant community composition as inferred from plant macrofossils recovered from ancient woodrat dens (middens), and from fossil pollen from dry cave, lake, fen and marsh sediments provide some of the best proxy data for past climate and some of its impacts.

Traditionally, changes in the species composition of plant communities have been used to infer shifts in paleoclimate. Diachronic variation in the relative abundance of the pollen of various plant species in stratigraphic records, and to a certain extent of the macrofossils of certain plants in woodrat middens, have been used to infer less dramatic responses of vegetation to changing climates spanning hundreds to thousands of years. Most recently changing plant productivity, as reflected in variations in short-term pollen production and confirmed by dendroclimatic studies, have led to the documentation of major climate shifts on the order of twenty-five years or less (Mehringer and Wigand 1990; Fritts and Xiangdig 1986).

SEMI-ARID WOODLAND PREHISTORY

Pleistocene (>11.5 ka)

Woodrat midden evidence indicates that semi-arid woodlands in the Intermontañe West appear to have been distributed as much as 500 to 640 km farther south, and 1,000 to 1,500 meters lower in elevation than at present during the glacial maximum around 18 ka (Van Devender and Spaulding 1979; Spaulding 1985; Wells 1983; Thompson 1990). Juniper or occasionally piñon-juniper woodlands occupied the Mojave Desert of southern California and southern Nevada, the southern Sierra Nevada, the southern Central Valley of California (Cole 1983; Thompson 1990), and the more arid regions of the Sonoran Desert in Arizona (Van Devender 1990). Farther north, juniper woodlands (characterized by Utah Juniper, but locally containing admixtures of Rocky Mountain and California juniper) dominated much of the western Great Basin as far north as the present location of Reno, Nevada (Wigand and Nowak 1992). Western Juniper (probably the southern variety) was growing in Kings Canyon, California, during maximum glaciation (Cole 1983). Western Juniper (probably the northern variety, *occidentalis*) also appears in the woodrat midden record on the east shore of pluvial Lake Lahontan in northwestern Nevada about 12 ka (the side receiving the benefit of lake effect rainfall) (Thompson et al. 1986). At the same time Utah Juniper characterizes the woodlands of the western and southern shores of the lake (Wigand and Nowak 1992).

In the northern Great Basin subalpine and/or tundra species of juniper (Prostrate Juniper, *Juniperus horizontalis*, and Common Juniper, *J. communis*) occurred in the Owyhee River Valley about 27 ka (Wells 1983). Its appearance in woodrat middens at relatively low elevations during what Benson et al. (1990) indicate was a warmer drier interstade implies that during the glacial maximum around 18 ka conditions may have been too harsh (too cold and/or dry) for Western Juniper (the current dominant) to survive in southeastern Oregon. Juniper pollen—probably of Common or Prostrate Juniper (through inference from its size and because of occurrence its macrofossils in contemporary woodrat middens)—from the Wetlands Levee Locality at Summer Lake south-central Oregon and from McCoy Flat near Eagle Lake, northern California provide further evidence of its presence in those areas between 12 and 50 ka years ago (Figures 1 and 2).

Further south in west-central Nevada both Western and Utah Juniper appear to have been present during the milder portions of the late Pleistocene (Thompson et al. 1986; Wigand and Nowak 1992). Absence of woodrat midden strata and the scarcity of pollen records dating to the glacial maximum precludes making definite inferences regarding the distribution of juniper on the landscape.

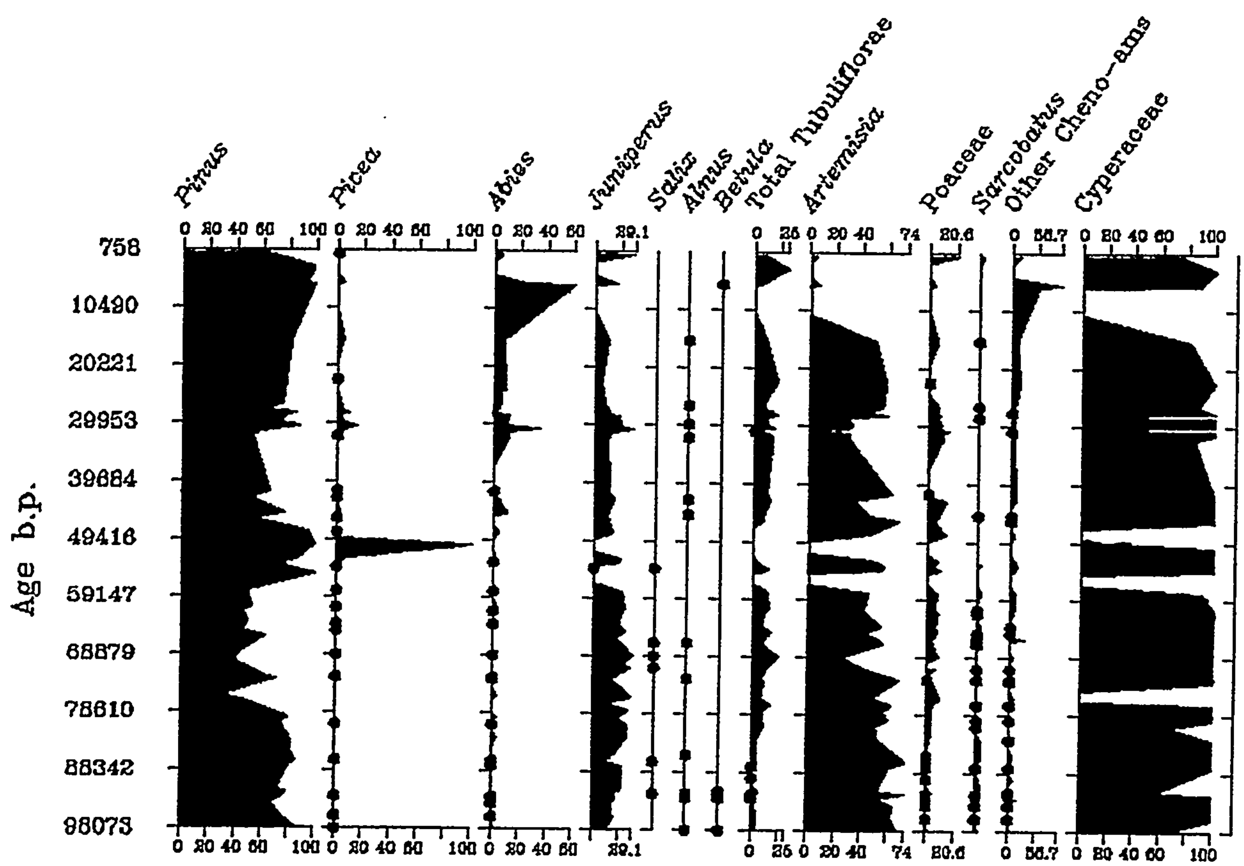

Figure 1. Relative percentage diagram of major pollen types from Wetlands Levee, Summer Lake, Oregon. Pine (Pinus) *percentage is plotted with respect to total terrestrial pollen. All other pollen types are plotted with respect to total terrestrial pollen minus pine pollen.*

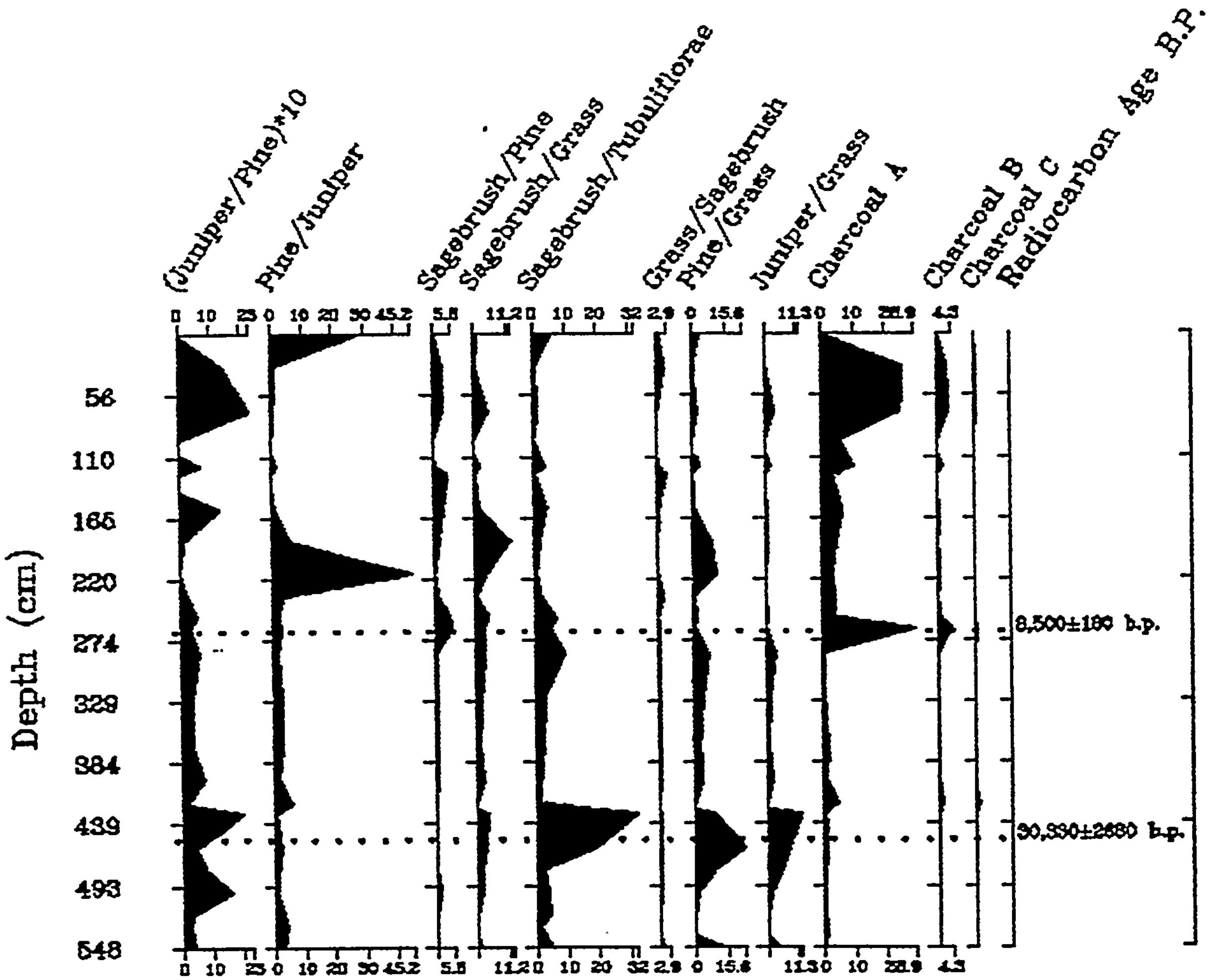

Figure 2. Ratios of major pollen types and charcoal plotted with respect to terrestrial pollen sum from McCoy Flat, Pine Creek, west of Eagle Lake, California.

However, greater shrub dominance in both the pollen and macrofossil samples from woodrat midden strata immediately prior to and following the glacial maximum suggests that juniper may have been relatively scarce occupying protected locations. On the other hand, shrub communities dominated by sagebrush, and at times saltbush, characterized extensive portions of the northwestern Great Basin (Wigand and Nowak 1992). These data suggest that it was either too dry or cold (or both) for juniper woodland to survive in the northern Great Basin during the last glacial maximum.

Early Holocene (11.5 to 8 ka)

The presence of semi-arid juniper woodland in the northern Great Basin at about 8.5 ka is evidenced by increased juniper pollen values in preliminary pollen records from Bicycle Pond at the foot of Hart Mountain in the Warner Valley of south-central Oregon and from McCoy Flat near Eagle Lake northern California (Figures 3 and 2). This is further corroborated by directly dated Utah Juniper twigs from woodrat middens in the Jackson Range of northern Nevada with a ^{14}C date of 8,490±90 b.p. (Beta-64360). By the beginning of the mid-Holocene the Bicycle Pond

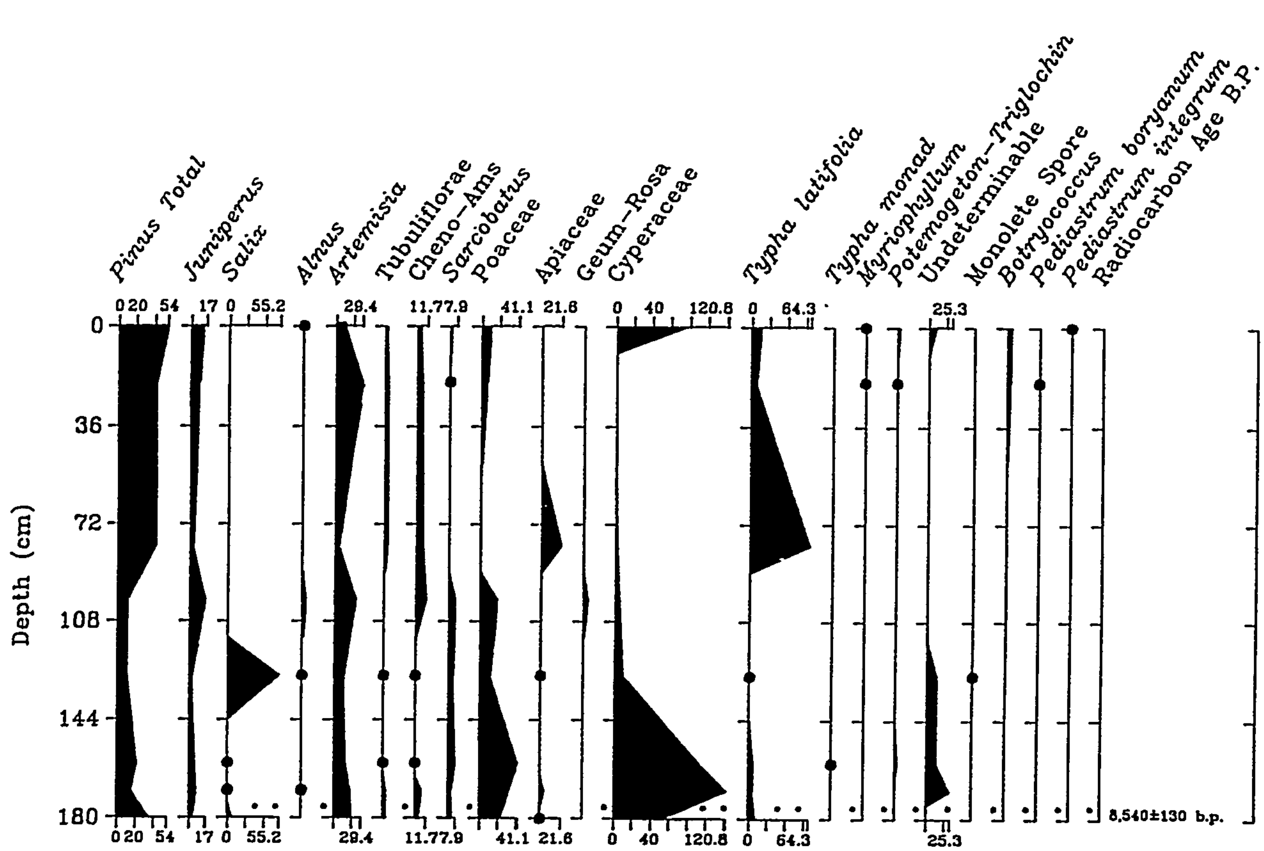

Figure 3. Relative percentage diagram of major pollen types from Bicycle Pond, Warner Valley, south-central, Oregon. All pollen types are plotted with respect to total terrestrial pollen.

and McCoy Flat records indicate that juniper woodland retreated upward and the sagebrush understory became the dominant vegetation at intermediate elevations.

Early Holocene persistence of Utah Juniper at lower elevations in northwestern Nevada was terminated ~ 9.5 ka during widespread, long-duration drought coinciding with the early Holocene global thermal maximum (Wigand and Nowak 1992). In southern Nevada replacement of Limber Pine-dominated subalpine woodlands by juniper-dominated semi-arid woodland at intermediate elevations precedes disappearance of low elevation juniper woodland by desert scrub (Wigand et al. 1994; Wells 1983; Thompson 1990; Thompson and Hattori 1983; Thompson and Kautz 1983) (Figure 4). Based upon the woodrat midden database Single-needle Piñon Pine (*Pinus monophylla*), although it appeared in several areas around southern Nevada including the Pahranagat Range by 8,500 b.p., seems to have been a much less important component of this early Holocene woodland than was juniper (Spaulding 1985; Thompson 1990) (Figure 4).

Middle Holocene (8 to 5.5 ka)

Woodrat midden evidence from the White Mountains on the California-Nevada border indicates that middle Holocene drought displaced semi-arid woodlands upward in elevation by as much as a 300 to 500 meters in large portions of the western Great Basin (Wigand and Nowak 1992; Jennings and Elliot-Fisk 1993). This coincides in age with drowned forests 10 to 15 meters below the

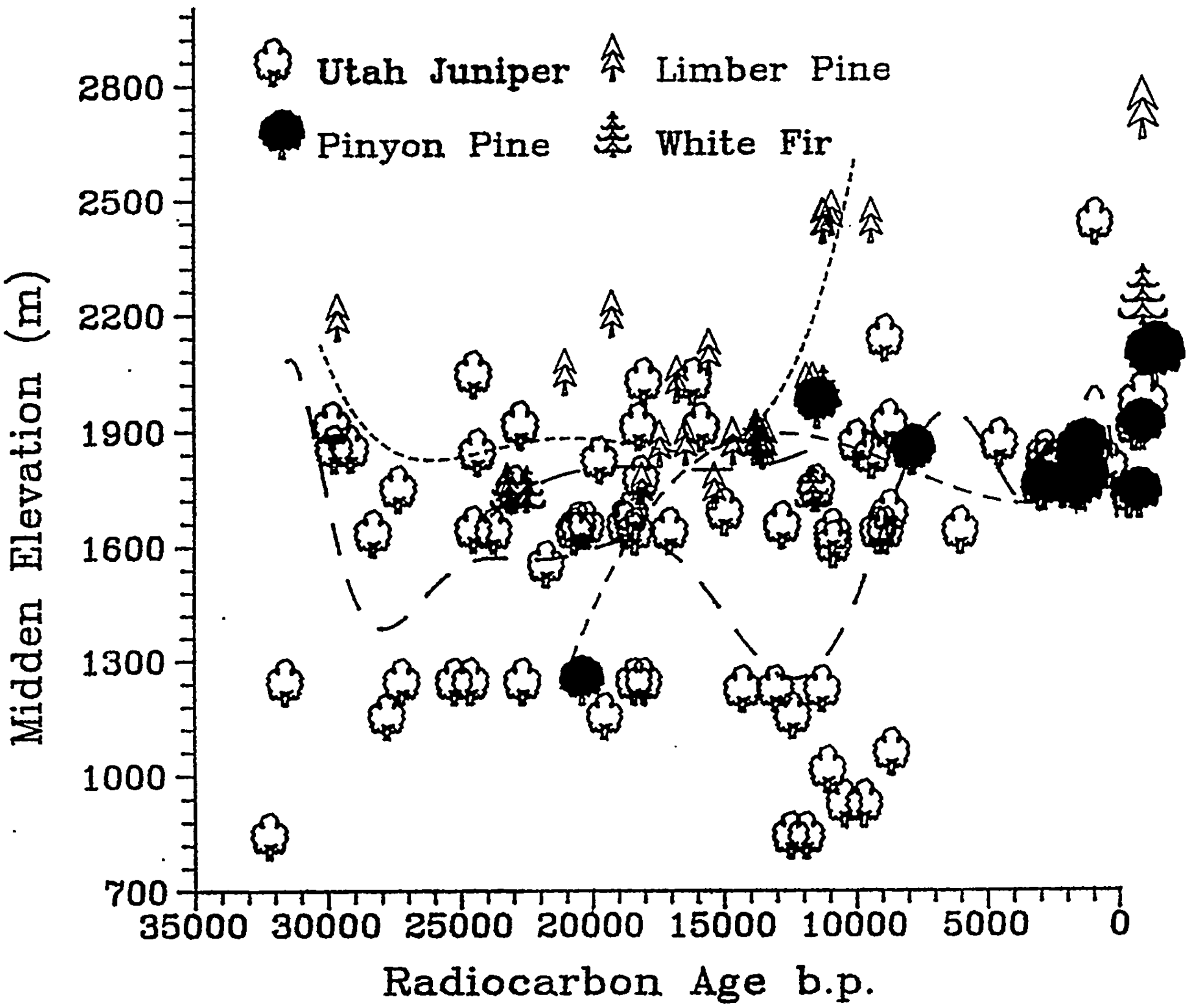

Figure 4. Elevational distribution of major tree species during the late Quaternary for the area around Yucca Mountain, southern Nevada. Larger tree symbols along the right margin of the diagram indicate the present distribution of these species in the Sheep Range north of Las Vegas. The post-Holocene transition from Limber Pine-dominated subalpine woodland to juniper-dominated woodland during the early Holocene and piñon-dominated woodland is evident.

modern surface of Lake Tahoe. These became established in the Tahoe Basin during periods of intense, long duration drought ~ 6.5 ka (Lindstrom 1990). Throughout the northern Great Basin lakes and marshes desiccated and pollen of drought-tolerant salt desert species increased substantially (Wigand 1987; Mehringer and Wigand 1990). Dramatically reduced evidence of the activities of Native populations is consistent with a decline in foraging resources and corroborates the severity of this drought (Aikens 1993).

Early Late Holocene (5.5 to 2 ka)

Beginning ~ 5.4 ka, this period of extreme drought came to an end with conditions remaining warm but with plant pollen and macrofossil data indicating gradually increasing winter and summer precipitation punctuated by dramatic but brief increases in rainfall abundance (Antevs 1938; Davis 1982; Wigand 1987; Mehringer 1986). The earliest evidence of Western Juniper reported in its historic range of northeastern California and eastern Oregon, are twigs from ancient woodrat middens at Lava Beds, California (5.4 ka) and Diamond Craters, Oregon (4 ka) (Mehringer and Wigand 1987; Mehringer and Wigand 1990). During the Neoglacial from 4 to 2 ka temperatures cooled and conditions were significantly wetter than present with winter precipitation dramatically increased with respect to summer precipitation (Wigand 1987; Davis 1982). Western Juniper woodland expansion in the northern-most Great Basin began about 4.5 ka as indicated by increasing juniper pollen values (Wigand 1987) (Figure 5). About 4 ka the rate of juniper woodland expansion increased dramatically culminating about 3.7 ka. Except for two or three lapses, Western Juniper woodland was

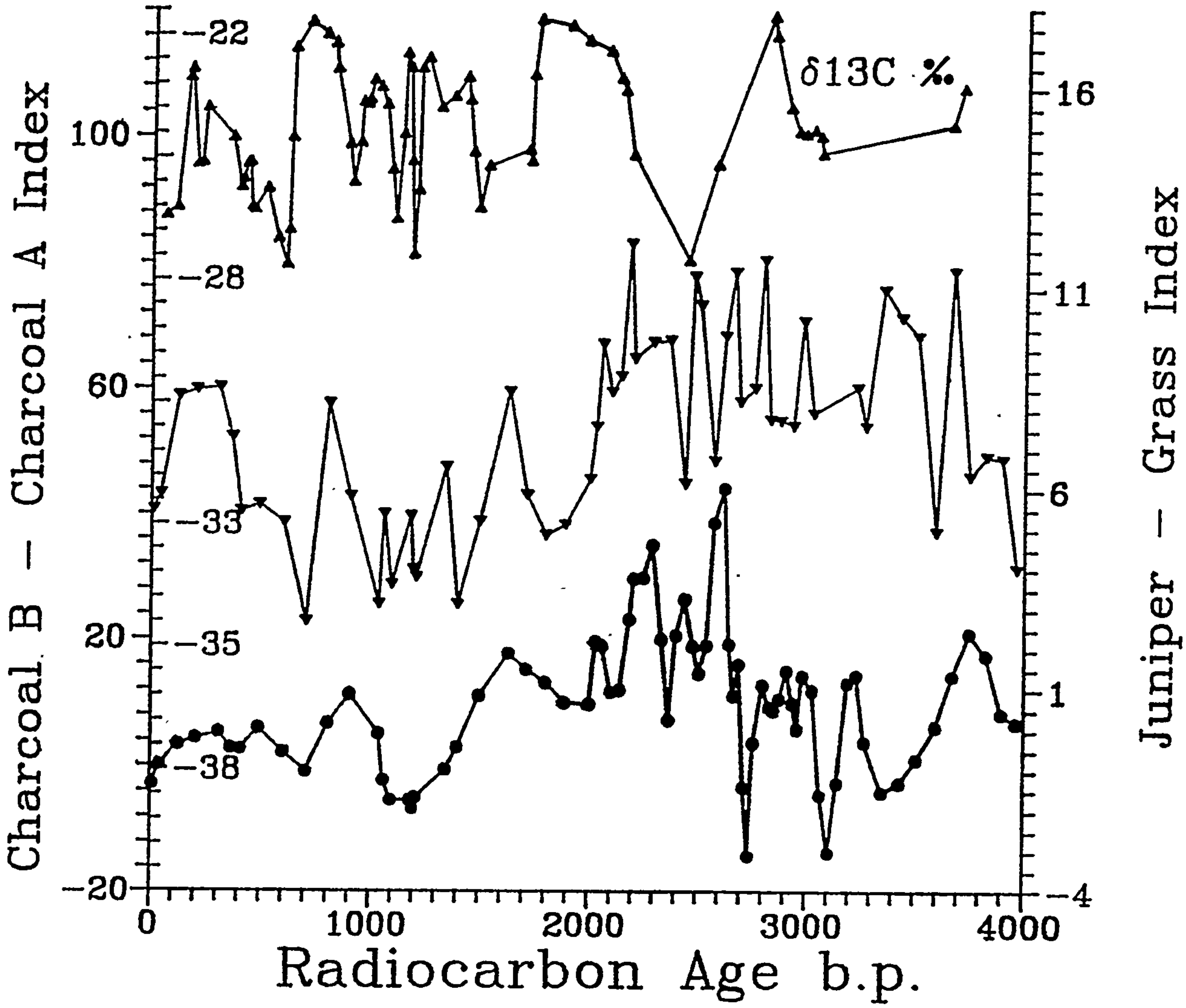

Figure 5. Comparison of (from bottom to top) ratio of large to small charcoal from the Diamond Pond record, ratio of juniper to grass and $\delta^{13}C$ values from the northern Great Basin. The circles with the solid line represent charcoal; the down-pointing triangles with the solid line represent the ratio of juniper to grass; and the up-pointing triangles with the solid line represent $\delta^{13}C$.

maintained at this extent until about 1.9 ka (Wigand 1987; Mehringer and Wigand 1990). Expansion of Western Juniper woodland during this period, primarily into lower elevation sagebrush steppe communities, entailed a drop of lower juniper tree line by as much as 500 feet. This is confirmed by Western Juniper macrofossils from woodrat middens (Mehringer and Wigand 1990).

The much more mesic conditions brought on by a combination of increased rainfall and lowered summer temperatures during this period would have promoted vigorous juniper growth (Fritts and Xiangdig 1986). Periodic increased abundance of grass pollen values in proportion to those of big sagebrush and salt desert shrub pollen during this period evidence a landscape dominated by a much more grassy sagebrush steppe than that of today with a sharp reduction in desert scrub vegetation as marshlands expanded into those areas (Wigand 1987; Mehringer and Wigand 1990).

Although juniper pollen values at Fish Lake on Steens Mountain above 2,200 m indicate a late middle Holocene upward elevational shift in juniper when conditions were still warm but increasingly wetter, lower Neoglacial juniper values suggest that no rise in upper juniper tree line occurred (Mehringer 1987; Mehringer 1985; Mehringer and Wigand 1987). Severe winter conditions, as evidenced by renewed alpine glacial activity, characterized this period and probably restricted juniper expansion at higher elevations.

Juniper pollen values from Diamond Pond indicate that during Neoglacial expansion, juniper woodland density at its lowest elevations was less than that of 20th-century Western Juniper woodlands at intermediate elevations (Wigand 1987). However, at intermediate elevations juniper was as thick or thicker than today (Davis 1981). Increased abundance of grass pollen coincident with woodland expansion also suggests the presence of a vigorous herbaceous understory. Although climatic conditions were good for juniper growth and establishment during this period at lower elevations, frequent drought-driven local and regional fires is evidenced by the charcoal recovered from pollen cores. Fire was promoted by an abundant herbaceous understory and probably helped maintain the low density of the woodlands (Wigand 1987; Miller and Wigand 1994).

Recent $\delta^{13}C$ data obtained on twigs of Western and Utah Juniper from ancient woodrat middens seem to indicate that although juniper woodland extent in the northern Great Basin was greater during the Neoglacial than today it was usually water stressed—either as a result of drought or frequent freezing during the growing season (Wigand et. al. 1994). In southern Nevada increased abundance of woodrat middens containing Utah Juniper and Single-needle Piñon Pine macrofossils evidence a major Neoglacial re-expansion and/or increase in density of Piñon-Juniper Woodland beginning ~ 3.8 ka (Figure 4). This expansion of semi-arid woodland culminates about 2.3 ka.

Mid Late Holocene (2 ka to recent)

Following the Neoglacial ~ 1.9 ka, Great Basin climate generally became warmer and drier (Wigand 1987; Wigand and Nowak 1992; Davis 1982; Wigand and Rose 1990). Juniper pollen values in the northwestern Great Basin declined dramatically with respect to grass (Wigand 1987). In addition, coarse to fine charcoal ratios fell reflecting the shift from juniper to shrub and forb fuels (Figure 5). Three very pronounced grass pollen increases tied closely to preceding charcoal events between 4 ka and 2 ka evidence dramatic local grass expansion after fire (Figure 5).

At higher elevations an increase in big sagebrush pollen relative to grass pollen reflects decreased grass in response to drier conditions (Mehringer 1987). An increase in desert scrub vegetation, indicated by increasing chenopod and greasewood pollen provides additional evidence for a period of increasing aridity, particularly between 1.9 and 1 ka (Wigand 1987). Pollen and macrofossils of aquatic plant species at Diamond Pond, Oregon indicate that water levels had dropped significantly since the Neoglacial (Wigand 1987).

Further south pollen records from Potato Canyon Bog near Austin, Nevada in the north-central Great Basin and two from the Sierra Nevada Mountains/Great Basin transition area, McCoy Flat near Eagle Lake, California and Little Valley near Washoe Lake, Nevada also evidence the Neoglacial expansion of semi-arid woodland after Neoglacial woodland expansion (Madsen 1985) (Figures 2 and 6).

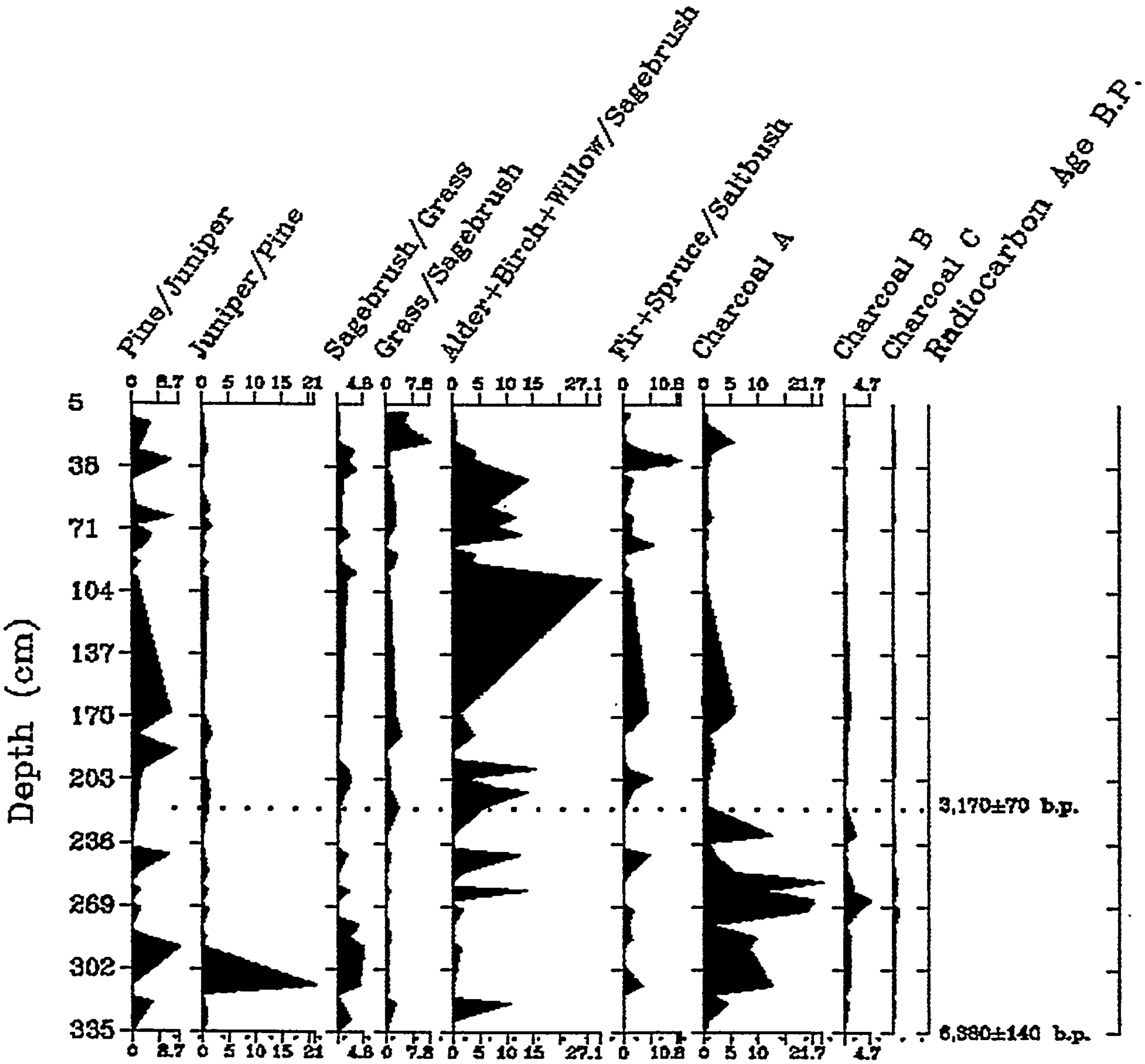

Figure 6. Ratios of major pollen types and charcoal plotted with respect to terrestrial pollen sum from Little Valley, Nevada near Washoe Lake, south of Reno, Nevada.

In the central Great Basin a 2,200-year pollen record from Lead Lake in the Carson Sink indicates that juniper and pine values declined dramatically from Neoglacial highs ~ 1.9 ka (Figure 7). Saltbush dominance at this time reflects low water to dry conditions in the Carson Sink. However the pollen record indicates that ~ 1.4 to 1.3 ka increased rainfall with a shift toward summer seasonality alleviated this drought. This resulted in an increase locally in piñon pine. The woodrat midden evidence indicates that piñon pine expanded both northward and downward (Figures 8 and 9).

The rapid change in piñon pine distribution may have been triggered by a combination of factors. The most important of these may have been increased rainfall throughout the summer to encourage seedling establishment. However, this expansion would probably not have been possible without the milder winter conditions that followed the end of the Neoglacial after 1.9 ka. After ~ 1 ka, the pollen record from Lead Lake indicates that there was a reduction in semi-arid woodland in the area (Figure 7). However, its elevational and latitudinal distributions seem to have been little affected.

At Lower Pahranagat Lake in southern Nevada a pollen record currently extending to 2 ka with a sample resolution of one every 14 to 15 years indicates that a piñon pine-dominated woodland began expanding about 50 to 150 years earlier than it did at Lead Lake (Figure 10). This may indicate that the shift toward summer season rainfall began earlier in the south than in the north and that movement of the northern boundary of these conditions may have taken several hundred years to reach the northern Great Basin. At Lower Pahranagat Lake, as at Lead Lake, the spread of woodland had reversed by 1 ka.

Significant increase in juniper pollen values ~ 1 ka in the northern Great Basin at Diamond Pond coincident with local increased abundance of woodrat middens containing Western Juniper macrofossils evidences a brief period of woodland expansion in the north (Mehringer and Wigand 1990; Wigand 1987).

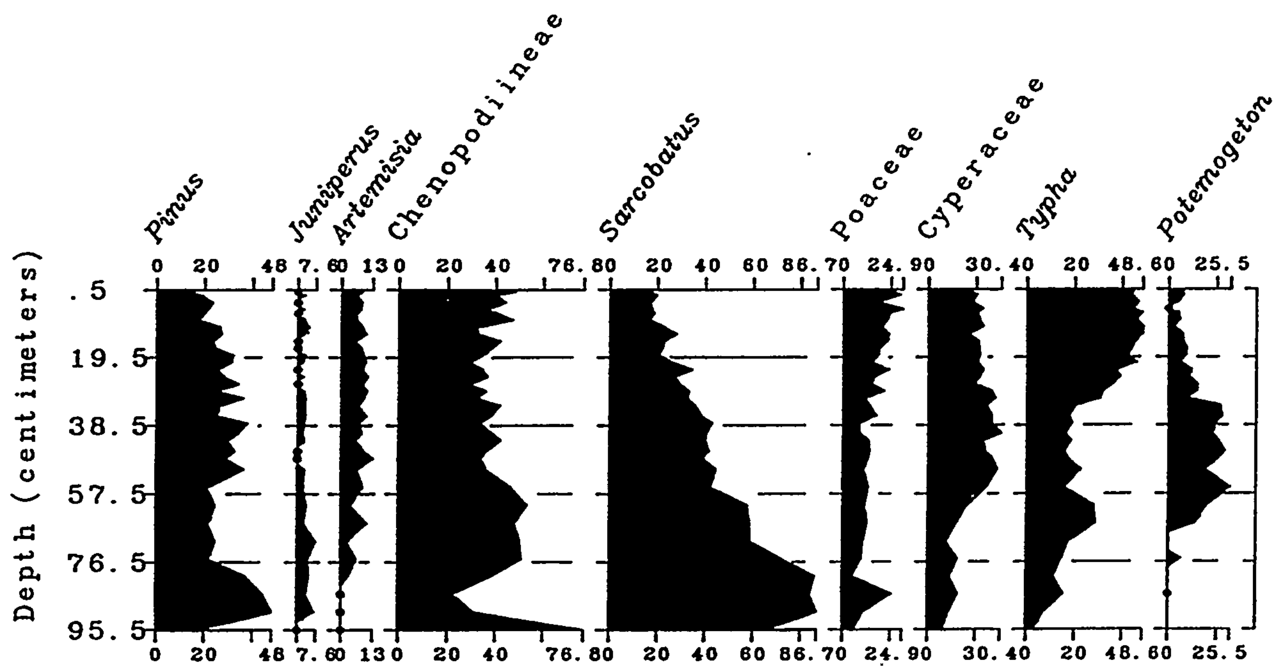

Figure 7. Relative percentage diagram of major pollen types from Lead Lake, Carson Sink, Nevada. All terrestrial pollen types are plotted with respect to total terrestrial pollen. Base of core dates to 2.1 ka with other radiocarbon dates indicating that the deposition rate is relatively uniform.

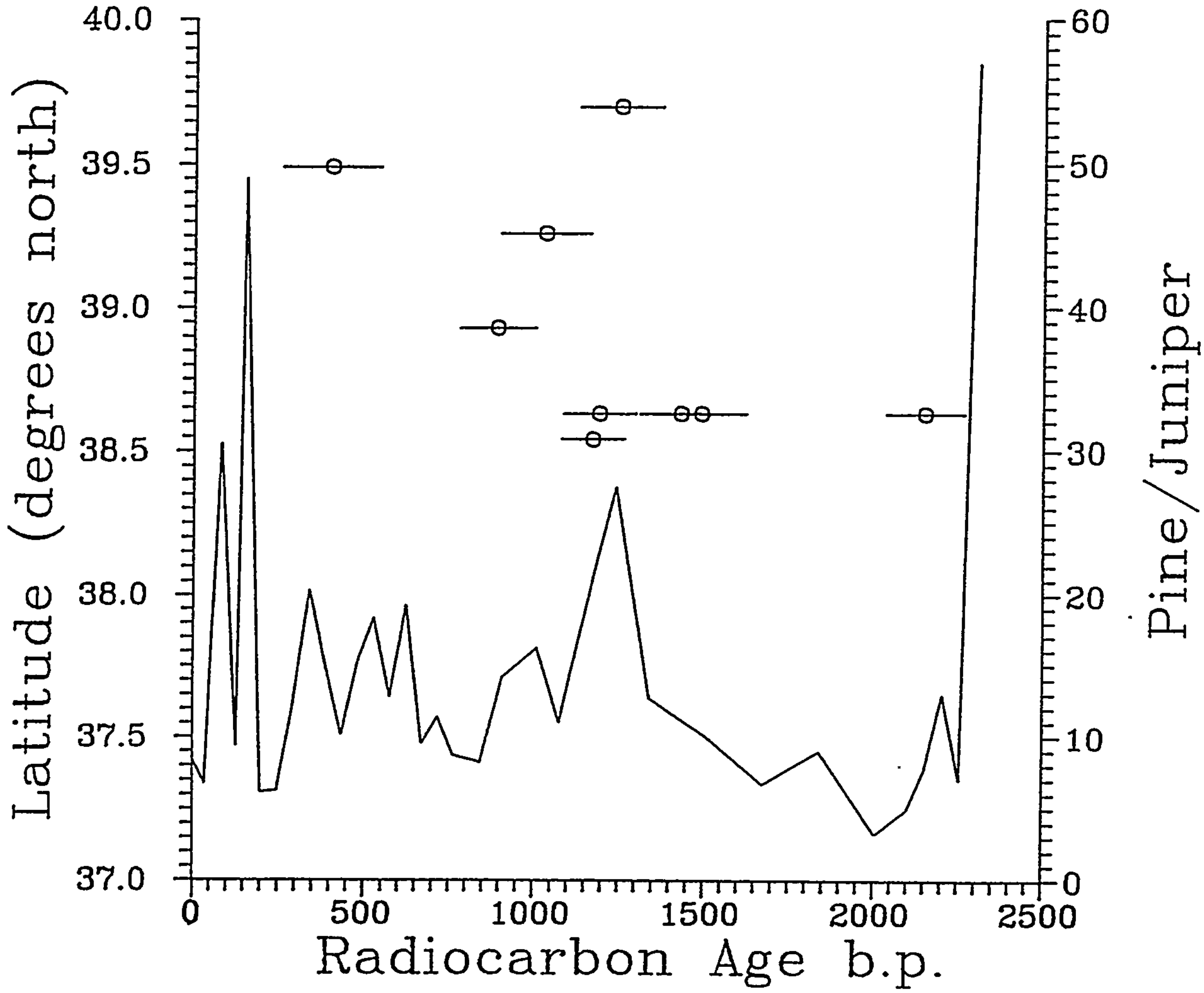

Figure 8. Ratio of pine to juniper pollen plotted against the latitudinal distribution of directly dated juniper twigs from woodrat middens in the Reno, Nevada area. Northward expansion of piñon during the last 1,500 years is evident.

This corresponds to increased large vs. small charcoal values indicating both a change in fuel type as well as more frequent fires as fuels build up in response to wetter climate (Figure 5).

Severe drought and resultant fire evidenced in the northern, central and southern Great Basin between ~ .9 and .5 ka, confirmed by Sierran and Great Basin tree-ring studies (Holmes et al. 1986) coincide with fire and dramatically reduced pollen values of juniper in the north (Wigand 1987) (Figure 5) and of juniper and piñon in the south (Wigand and Rose 1990) (Figures 10 and 11). Additional evidence of severe drought in the Mono Lake Basin occurs at this time (Stine 1990).

Dramatic retreat of Great Basin woodland is indicated by these data. Even a sudden gap in the woodrat midden evidence for this period seems to reflect woodland decline (Wigand and Nowak 1992).

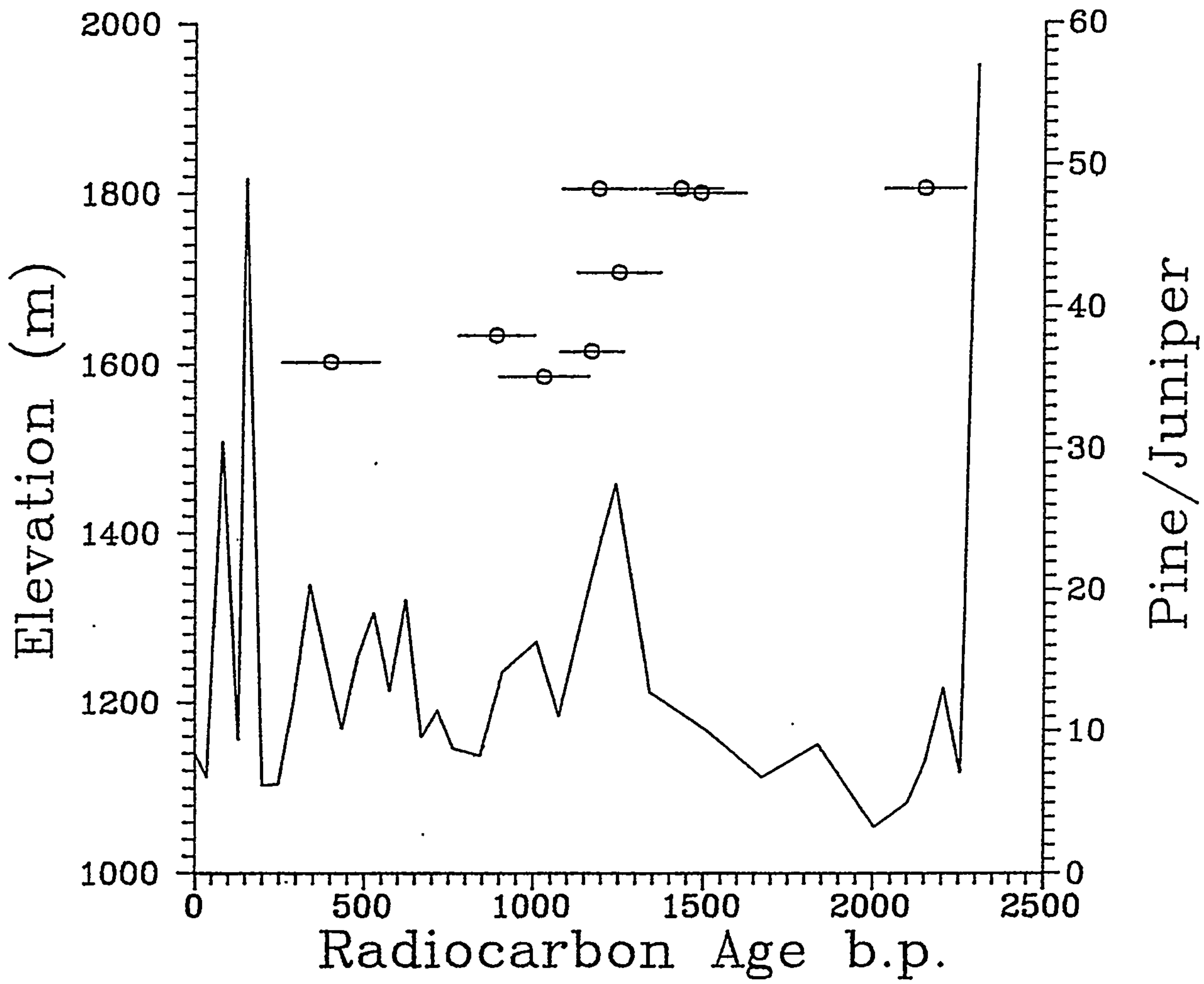

Figure 9. Ratio of pine to juniper pollen plotted against the elevational distribution of directly dated juniper twigs from woodrat middens in the Reno, Nevada area. Lower elevational distribution of juniper during the last 1,500 years is indicated.

The "Little Ice Age," a pattern of stronger winter precipitation and cooler temperatures beginning 300 to 400 years ago, initiated a gradual re-expansion of juniper woodland in the northern Great Basin (Mehringer and Wigand 1990). Further south in the central and southern Great Basin increasing pine pollen values with respect to juniper pollen values indicate that piñon benefitted more from the shift toward mesic climate conditions (Wigand and Nowak 1992) (Figures 12 and 10). By the time Europeans first entered the area, climate initiated re-expansion of Great Basin woodlands was well under way.

Recent

Evidence from relict juniper woodlands, tree-age class ratios, fire scars and historical documents indicate that prior to the 1800s piñon-juniper and juniper woodland distribution and structure was much different than at present. Density of old trees, early reports by trappers and settlers, and old photographs suggest that

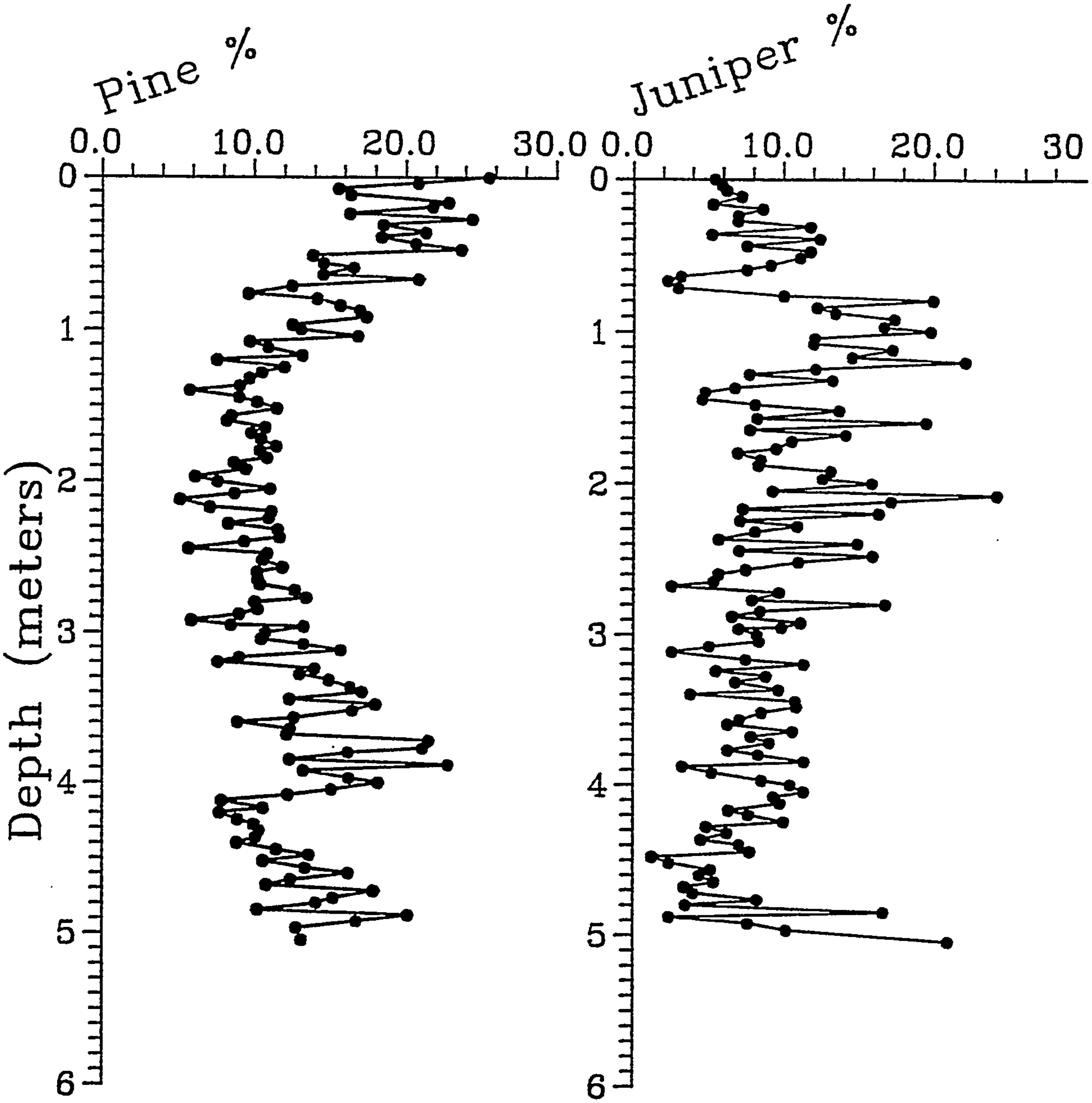

Figure 10. Preliminary relative percentage diagram of pine and juniper values from Lower Pahranagat Lake, White River Valley, southern Nevada plotted by depth. The base of the record is 1.9 ka.

junipers usually formed savannahs rather than dense woodlands (West 1984).

Western Juniper less than 40 to 50 years old are easily killed by fire (Burkhardt and Tisdale 1976). During drier climatic periods and at lower elevations fire probably maintained both shrubs and trees at low densities providing a savannah-like appearance to much of the landscape prior to European settlement (Burkhardt and Tisdale 1976). The presence of old-growth trees exclusively on rocky sites is probably due to low levels of fine fuel limiting fire.

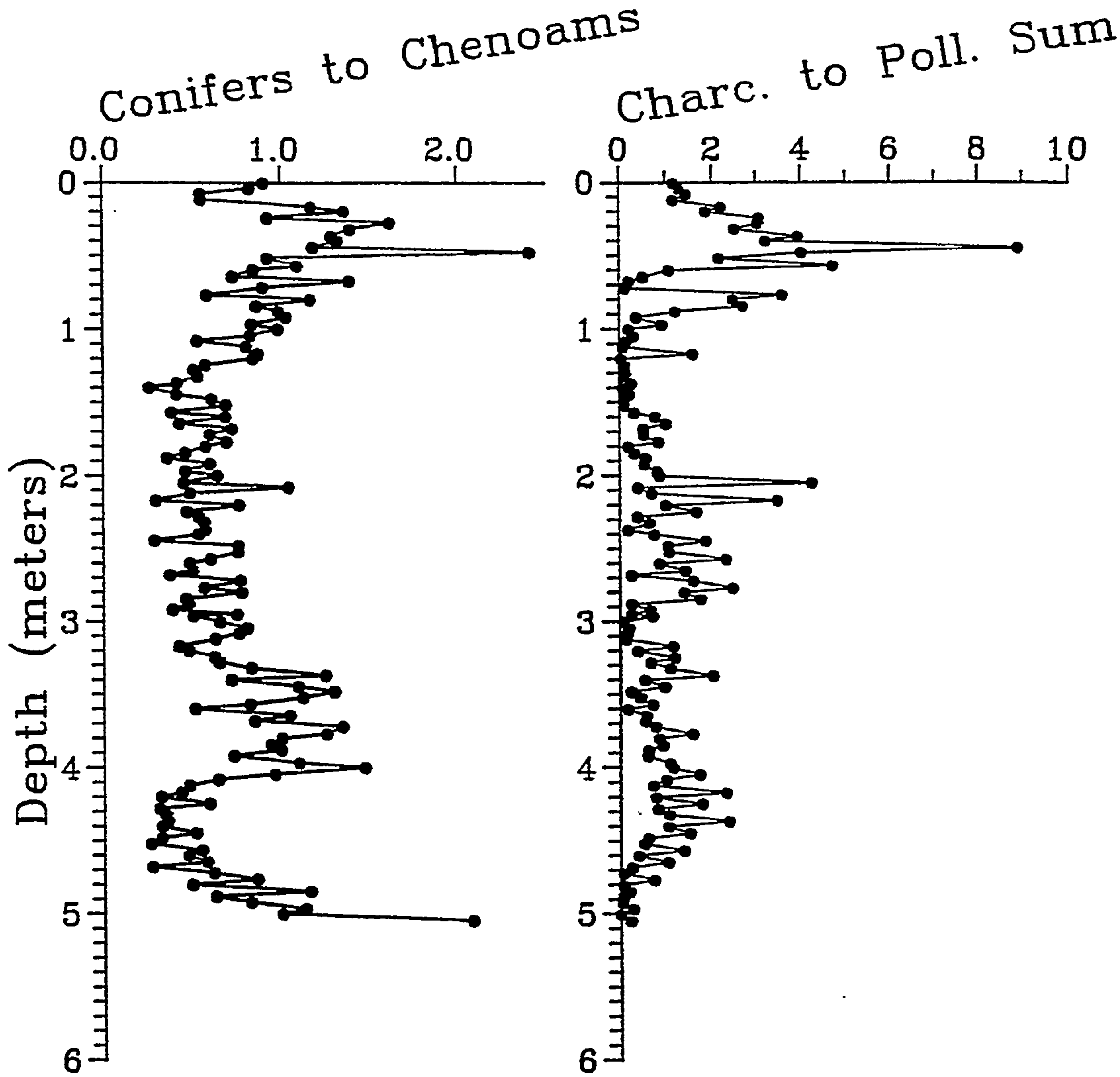

Figure 11. Preliminary relative percentage diagram of conifers to chenoams (saltbushes), a drought measure and total charcoal to terrestrial pollen sum, a measure of regional fire activity, from Lower Pahranagat Lake, White River Valley, southern Nevada plotted by depth. The base of the record is 1.9 ka.

However, during the past 150 years, juniper species have increased both in distribution and density throughout their range in the Intermontañe region (Tausch et al. 1981; West 1984; Cottam and Stewart 1940; Blackburn and Tueller 1970; Miller and Rose 1993). Expansion has occurred into open meadows, grasslands, sagebrush steppe communities and aspen groves (Cottam and Stewart 1940; Johnsen 1962; Blackburn and Tueller 1970; Eddleman 1987; Miller and Rose 1993; Hastings and Turner 1965).

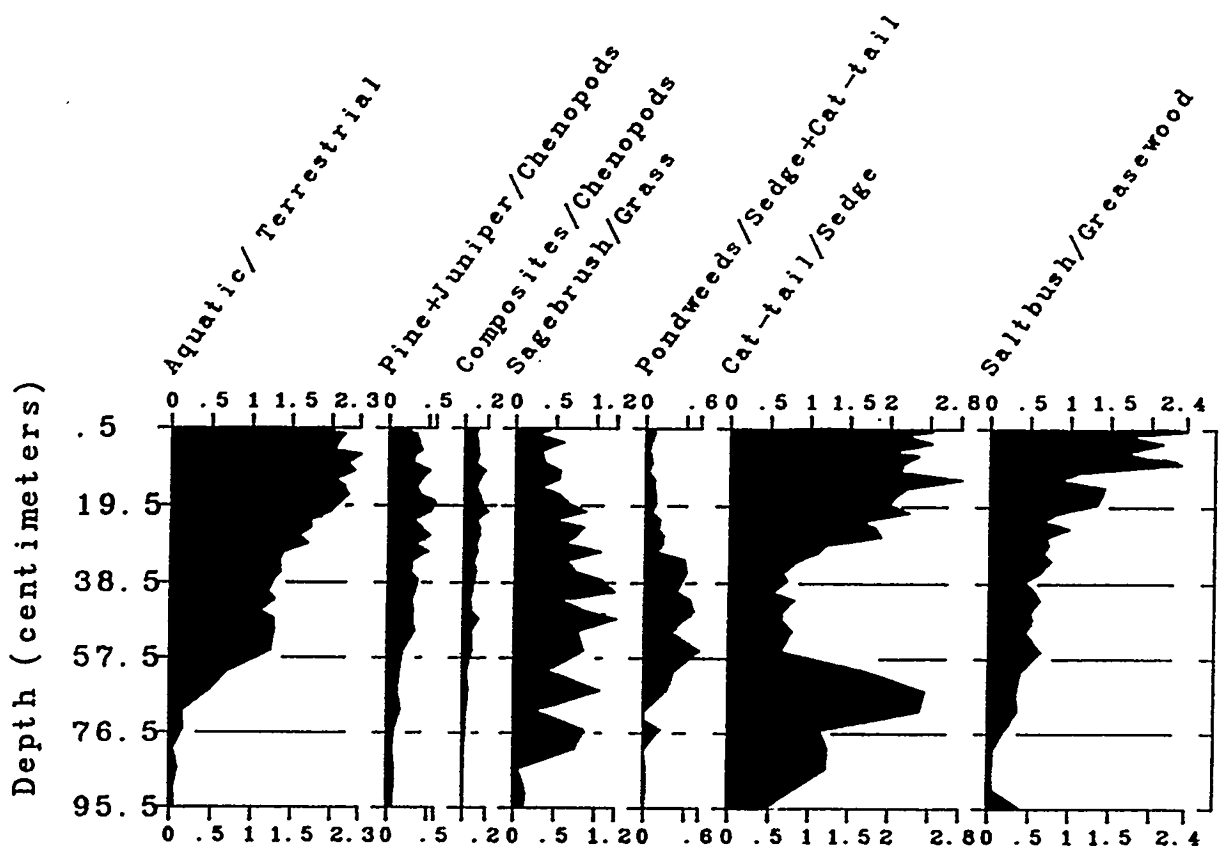

Figure 12. Ratios of major pollen types from Lead Lake, Carson Sink, Nevada. Base of core dates to 2.1 ka with other radiocarbon dates indicating that the deposition rate is relatively uniform.

In 1901 Griffiths observed only scattered stands of Western Juniper on Steens Mountain (though some of these were up to 600 years old) in southeastern Oregon (Griffiths 1902). Western Juniper began increasing in both density and distribution in the late 1800s (Young and Evans 1981; Eddleman 1987; Miller and Rose 1994). Western Juniper currently occupies more than 1 million ha in eastern Oregon, southwestern Idaho, and northeastern California. As a result, although Western Juniper is a long lived species—nearly 3 ka (Lanner 1984)—the majority of its present day woodlands are less than 100 years old throughout its range. Density of trees less than 100 years old on these rocky low sagebrush flats and recently occupied Mountain Big Sagebrush (*Artemisia tridentata vaseyana*) communities average 338/ha.

In southwestern Utah between 1864 and 1940, piñon-juniper woodlands expanded down-slope covering fivefold as much land area and tree densities increasing 6 to 20 times that of the original piñon-juniper stands (Cottam and Stewart 1940). In Nevada, a basin-wide survey of piñon-juniper woodlands showed that tree populations (primarily piñon) have increased in density and almost 2.5 fold in areal distribution during the past 150 years (Tausch et al. 1981).

Since the "Little Ice Age" mean annual temperature has been rising (Ghil and Vautgard 1991). This is indicated at Diamond Pond in south-central Oregon by an increase in sagebrush pollen relative to grass pollen reflecting an increase in regional sagebrush abundance with respect to grass. A decrease in the depth of Diamond Pond at this time indicates a regional drop in water table in the Harney Basin near Steens Mountain (Mehringer and Wigand 1990; Wigand 1987). Fluctuating juniper pollen values in the early 1800s contrast with a recent sharp increase since the mid-1900s (Mehringer 1987; Mehringer and Wigand 1990). Although this increase may in part reflect a real expansion in woodland, it may also simply be the artifact of closer sampling interval.

The post "Little Ice Age" trend toward lower effective precipitation brought on by warmer mean annual temperatures combined with the spread of woodlands should have increased the potential for fire in the Great Basin. Although drought stress on the trees comprising the semi-arid woodland should have provided ideal conditions for increased fire frequency, the occurrence of fire decreased during this period. This stands in contradiction to the prehistoric pattern of massive fires that typified periods when Great Basin woodlands were subjected to drought conditions, i.e., the end of the Neoglacial and during the lengthy droughts of the 1300 and 1400s.

In part decreased fire frequency may have occurred because conditions were dry enough to keep the production of light fuels, i.e., grasses and forbs and even shrubs, low. On the other hand, Peter Skene Ogden noted abundant evidence of Native American-set fires in the Harney and Malheur lakes region during the middle 1820s (Davies et al. 1961). A decline in Native American fires as native populations shrank may have led in part to reduction of fire frequencies and enabled the expansion of semi-arid woodlands at the time of European settlement. Livestock grazing may also have played a role in decreased fire frequency through the reduction of fine fuels. Grazing may also have played a role in juniper expansion through seed dissemination and encouragement of shrubs which provided nursery areas for juniper seedling establishment.

Fence lines built to enclose cattle may also have encouraged this expansion, because fence-lines provided roosting sites for juniper seed-eating birds. Juniper groves tracing old fence lines are quite common in the northern Great Basin. Finally, reduced fire frequency also has been suggested as one of the primary factors responsible for the historic expansion of juniper throughout the West (Johnsen 1962; Blackburn and Tueller 1970; Burkhardt and Tisdale 1976; Young and Evans 1981).

CONCLUSIONS

Prehistorically climate change was the primary factor effecting the expansion of semi-arid woodlands. Droughts and resultant disturbance phenomena such as insect infestations, disease and fire all contributed to periodic retrenchments of these woodlands. Since European arrival woodland expansion has been effected by climate change and human activities.

Drier climates during this century have resulted in increased physiological stress on the plant communities. Normal cycles of disturbance phenomena such as fire, insect infestation and disease have been disrupted by fire suppression practices, and the use of insecticides. Resulting fuel build up has increased the potential for intense, widespread fires.

Periods of wetter climate around 1910, the early 1940s, the late 1960s and early 1970s, and the early 1980s have served to briefly revitalize these woodlands. However, if the drought of the last seven years is near the climatic norm for the last millennium—as Sierran tree-ring records and pollen data from the Great Basin suggest (Graumlich 1993)—retrenchment of semi-arid woodlands to higher elevations and continuation of the trend toward reduction in grasses and expansion of sagebrush can be expected in the future.

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CHARACTERIZATION AND POSSIBLE ORIGINS OF ISOLATED DOUGLAS FIR STANDS ON THE COLORADO PLATEAU

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Keywords: *dispersal, flora, relicts, vegetation, late Wisconsin*

ABSTRACT

The floristic composition of several isolated stands of Pseudotsuga menziesii on the Colorado Plateau is compared. All occurred between 1700–2000 meters, which was about 300–500 meters below typical lower limits for the species. Most stands showed evidence of reproduction and recruitment. A small widespread group of species existed that was common to all stands, but beta diversity was high. A preliminary analysis of possible origins of the stands suggested that they are relictual from the late Wisconsin or early Holocene. Bird-dispersed species were less prevalent than expected compared with existing high elevation conifer forests. These stands represent important resources for Quaternary research, but are extremely vulnerable to human-caused disturbances. It is recommended that they be provided protection from disturbance through appropriate management activities of the various land management agencies.

INTRODUCTION

The vegetation and flora of the Colorado Plateau is a product of many factors, chief among them being the semi-arid to arid climate, the great variety of sedimentary strata, and climate change (Welsh 1978; Betancourt 1990; Schultz 1993). Floristically, the plateau is highly distinctive (McLaughlin 1989). It is a major center of speciation and endemism in herbaceous taxa, and supports a rich flora of some 2000 species. Although there are obvious relationships with the Great Basin, and the higher elevations support many Rocky Mountain taxa, the Colorado Plateau remains floristically distinct, with only weak ties to surrounding provinces. Much of the endemism may stem from climatic variability during the Pleistocene working on isolated populations in the topographically complex landscape of the Colorado Plateau. There is considerable evidence for climate change on the Colorado Plateau from alluvial sequences and pack rat middens (Betancourt 1990). At approximately 12,000 yrs BP, much of the central plateau probably supported mixed woodlands of limber pine (Pinus flexilis) and Rocky Mountain juniper (Juniperus scopulorum) on dry sites, interspersed with parklands of sagebrush (Artemisia species). In wetter sites such as along streams in canyons, mesic-site conifers like Douglas fir (Pseudotsuga menziesii), white fir (Abies concolor), and blue spruce (Picea pungens) were found. Associated with these riparian sites were deciduous tree species like maples (Acer species), western birch (Betula occidentalis), and Gambel oak (Quercus gambelii). Withers and Mead (1993) recorded many of these species from alcoves in the Escalante River area with associated radiocarbon dates ranging from

8,000–13,000 yrs BP. Climate changes associated with the transition from the late Wisconsin to the early Holocene resulted in the elimination of these woodlands below their current elevational limits, which vary, depending on species, from 2200–3000 m on the central Colorado Plateau.

The higher elevations of all the mountain ranges on the Colorado Plateau support extensive populations of Douglas fir. The lower elevational limits for this species is generally at or above 2300 m along streams, and somewhat higher on dry sites. However, small isolated stands of Douglas fir occur at elevations well below this. These disjunct stands are found in protected alcoves along canyons as low as 1700 m. Associated as understory components of these tree stands are other montane taxa that are normally found at much higher elevations on the Colorado Plateau. The origins of these isolated stands is currently not well understood. There are two hypotheses that can explain the presence of these disjunct montane species. First, they may be relictual populations from a period when conditions were cooler and wetter on the Colorado Plateau. Paleoclimatic reconstructions suggest that the late Wisconsin was the last time that climates would have allowed extensive populations of these species to exist below 2000 m on the central Colorado Plateau. An alternative hypothesis is that these stands are the result of recent dispersal events from populations on the nearby mountain ranges. The only dispersal mechanism that would operate over the distances involved (30–50 km or more from sources in the mountains) is bird dispersal, although wind dispersal of spores may be possible for fern species.

In this paper, I describe the floristic composition and vegetation of five isolated stands of Douglas fir from the central Colorado Plateau. Preliminary tests of the relictual and dispersal hypotheses are presented. Finally, the importance of these stands for understanding species responses to climate change, as well as possible future work, is discussed.

METHODS AND MATERIALS

Five sites were selected based on accessibility. One site, Shafer Alcove, is in the Island in the Sky district of Canyonlands National Park (NP). The remaining four sites are in Glen Canyon National Recreation Area (NRA); Miller's Canyon at the south end of the Waterpocket Fold (documented in detail in Spence 1992), and Millard Canyon and two sites in French Spring Fork of Happy Canyon, in the Orange Cliffs district of Glen Canyon NRA. The Millard Canyon site is ca. 5 km from the two sites in French Spring Fork. These two latter sites are in alcoves ca. 1 km apart. The Shafer and upper Miller's Canyon sites are isolated by distances of greater than 50 km from any other site. All sites were visited between 1992 and 1994. At each site, the number of Douglas fir trees was counted, and diameter at ground level (dgl) of each tree was measured (data not reported here). Seedlings were defined as individuals with a dgl of less than 1 cm. Understory vegetation was described using the relevé technique of Rowlands (1994). Species were classified by probable dispersal mode using the classification of Spence and Henderson (1993). Dispersal types were grouped into two categories: bird dispersed and all others. Categorization of species by pollination mode and probable breeding system were based on floral syndromes. Disjunct species are defined as species that normally occur at higher elevations (montane or above) on the Colorado Plateau. For comparisons with montane forest vegetation, species lists were compiled from data presented in Youngblood and Mauk (1985) and Padgett et al. (1989). The first 100 species encountered in the data tables in these publications, for both upland and riparian Douglas fir vegetation, were compiled and classified by dispersal category. All species selected are known to occur on the Colorado Plateau. Finally, data on disjunct species associated with riparian zones and springs around Lake Powell (Spence 1995), were compared with the Douglas fir sites and the two sets of 100 species. Nomenclature follows Welsh et al. (1993).

Site floras were compared using Jaccard's coefficient of similarity, which computes the floristic similarity between two areas by:

$$S_J = [c/(a+b+c)] \times 100$$

where c is the number of species in common to two sites, a is the number of species unique to the first site, and b is the number of species unique to the second site. High values indicate many species in common, low values very few species in common. In order to set confidence limits around S_J, Monte Carlo simulations were run. In this simulation, all species from the five sites were pooled. The composition of each site flora was then reconstructed by random draws from the pool. Random S_J values were then computed between each pair of random site floras. This process was repeated 20 times. Confidence intervals (CI) were then constructed for a 95% two-tailed test. The real S_J values can fall outside the analogous random S_J for each pairwise comparison, or be within the 95% CI. Details on Monte Carlo simulations on association measures can be found in McCoy and Heck (1987) and Spence and Henderson (1993). Although random expectation may not always be biologically realistic, it does provide a baseline against which to compare significant departures that may be biologically meaningful.

RESULTS

1. Site descriptions

Table 1 summarizes site information. All stands occurred in north, northeast to northwest facing alcoves at the base of Navajo Sandstone cliffs, associated with springs. Elevations ranged from 1770 m to 1920 m. The substrate at all sites consisted of eolian sand deposits with some colluvium. Organic soils were evident over the deposits at the Miller's Canyon site. Numbers of Douglas fir individuals varied from 20-92. All sites except the Shafer Alcove showed evidence of reproduction by the presence of seedlings. The number of disjunct montane species varied from six to nine (see Table 2 and below). The dominant understory species associated with the Douglas fir was different in each stand.

2. Floristics

Table 2 lists the disjunct species found in the five alcoves. Some of these are elevationally widely distributed species associated with springs rather than directly with the Douglas fir. These are classified as wetland species rather than montane disjuncts. However, all species listed in Table 2 survive in the alcoves primarily because of the extra moisture supplied by the springs. In addition to Douglas fir, five species were found at all sites; Aquilegia micrantha, Carex rossii, Calamagrostis scopulorum, Habenaria zothecina, and Holodiscus dumosus. Ten species were restricted to a single site, with five of these at upper Miller's Creek. Several understory species appear to be directly associated with the Douglas fir, as they are not found elsewhere. These include Acer glabrum, Berberis fendleri, Cornus sericea, and Ribes sp. Most other species in Table 2 occur in other sites not in association with Douglas fir. In addition to those listed, numerous upland species characteristic of pinyon-juniper woodlands and arid shrublands were also found in the alcoves.

Floristic comparisons showed two distinct patterns (Table 3). The three sites FS1, FS2, and MIC were floristically similar, with S_J's of 73%–80%. The more isolated SHA and UMC sites were floristically more distinct from these three sites as well as each other (S_J's of 28%–40%). Monte Carlo simulations indicated that FS1, FS2, and MIC were significantly more positively related than expected by chance alone, while all other comparisons fell within the 95% confidence intervals of the random S_J's.

3. Vegetation

Standard relevés were described for the five sites. Summary data is shown in Table 4. In

Table 1. Summary of selected characteristics for the alcoves associated with Douglas fir stands. Tree data were not collected at FS2.

	Site[1]				
Feature	UMC	MIC	FS1	FS2	SHA
ASPECT[1]	010	310	000	355	350
SPRING PRESENT	yes	yes	yes	yes	yes
ELEVATION (m)	1770	1890	1890	1920	1800
NUMBER OF DOUGLAS FIRS	92	70	60	20	42
MEAN DGL (cm)	36.2	32.7	21.0	-	40.0
LARGEST DGL (cm)	113.5	85.1	121.9	-	99.1
DOUGLAS FIR SEEDLINGS PRESENT	yes	yes	yes	yes	no
% OF POPULATION THAT ARE SEEDLINGS	11%	6%	18%	-	0%
NUMBER OF DISJUNCT MONTANE SPECIES	9	7	7	7	6
VEGETATION TYPE[2]	PSME-ACGR	PSME-COSE	PSME-ROWO	PSME-QUGA	PSME-ACGL

[1]In degrees east of true north.

[2]PSME=Pseudotsuga menziesii; ACGR=Acer grandidentatum; COSE=Cornus sericea; ROWO=Rosa woodsii; QUGA=Quercus gambelii; ACGL=Acer glabrum.

all, 33 species were encountered in 10 relevés. All sites consisted of a rather sparse overstory of Douglas fir with scattered shrubs in the understory. The most common understory species differed from site to site. The upper Miller's Canyon (UMC) site consisted of a dense layer of Acer grandidentatum and Ostrya knowltonii, and also had the densest stand and resultant canopy cover of Douglas fir. The remaining sites consisted of many fewer scattered Douglas fir which produced less shade.

The understories of these sites consisted of sparse layers of shrubs with scattered forbs and graminoids. Small streams traversed the UMC and FS2 sites. Along these streams species like Apocynum cannabinum, Cystopteris fragilis, Habenaria zothecina, and Smilacina stellata occurred. In all sites except Millard Canyon, the combined importance values of the disjunct montane species were higher than combined values for arid and semi-arid species.

Table 2. List of disjunct species associated with Douglas fir at each site. Montane disjuncts are those species that occur well below their normal elevational limits on the Colorado Plateau. Wetland species are those species found at various elevations in scattered populations associated with springs and perennial riparian zones. Montane disjuncts can be either upland or wetland species.

	Site[1]				
Species	UMC	MIC	FS1	FS2	SHA
Montane disjuncts					
Acer glabrum	-	-	-	-	+
A. grandidentatum	+	-	-	-	-
Amalanchier alnifolia	-	+	+	+	-
Berberis fendleri	-	-	-	-	+
Calamagrostis scopulorum	+	+	+	+	+
Carex rossii	+	+	+	+	+
Cornus sericea	-	+	+	+	-
Cystopteris fragilis	+	-	-	-	-
Holodiscus dumosus	+	+	+	+	+
Mahonia repens	+	-	-	-	-
Pseudotsuga menziesii	+	+	+	+	+
Ribes sp.	+	-	-	-	-
Rosa woodsii	+	+	+	+	-
Wetland species					
Acer negundo	-	-	+	-	-
Adiantum capillus-veneris	+	-	-	-	+
Apocynum cannabinum	-	+	+	+	-
Aquilegia micrantha	+	+	+	+	+
Habenaria zothecina	+	+	+	+	+
Mimulus eastwoodiae	+	-	-	-	+
Ostrya knowltonii	+	-	-	-	-
Primula specuicola	-	-	-	-	+
Rhamnus betulifolia	-	+	+	-	-
Salix lutea	-	-	-	+	-
Smilacina stellata	+	-	+	+	-
Solidago sparsiflora	-	+	-	-	+
Toxicodendron rydbergii	+	+	+	+	-
Total species/site	16	13	14	13	12

[1]UMC=Upper Miller's Creek, MIC=Millard Canyon, FS1=French Spring Fork of Happy Canyon alcove 1; FS2=French Spring Fork of Happy Canyon alcove 2; SHA=Shafer Alcove.

Table 3. Jaccard's coefficient of similarity (%) among five stands of Douglas fir. Above and to the right of the diagonal results of a Monte Carlo simulation of floristic similarity is presented (refer to "Methods and Materials").

	Site				
	(1)	(2)	(3)	(4)	(5)
(1) UMC	—	0[1]	0	0	0
(2) MIC	33.3	—	+[2]	+	0
(3) FS1	38.1	80.0	—	+	0
(4) FS2	40.0	73.3	80.0	—	0
(5) SHA	33.3	36.8	28.6	30.0	—

[1]Indicates that the real floristic similarity is within 95% confidence for random expectation.

[2]Indicates that the real floristic similarity is outside the 95% confidence intervals for random expectation and is larger.

4. Life form analysis and dispersal ecology

Montane disjuncts in the Douglas fir stands were predominantly woody species (77%; Table 5). In contrast, woody species accounted for 45% and 35% of the montane upland and wetland species groups, respectively. Herbaceous species were most common in the alcove site wetland species (62%) and montane wetland Douglas fir (65%) groups. Herbaceous species were more widespread (average of 3.1 sites) than woody species (2.3 sites).

Bird-dispersed species comprised from 25–38% of the species in the four groupings (Table 5). These included species which produce brightly colored fleshy berries, hips, or pomes, e.g., Amalanchier alnifolia, Apocynum cannabinum, Cornus sericea, and Rosa woodsii. Most of the dominant tree species in the Douglas fir stands, however, were wind dispersed, e.g., Acer glabrum, A. grandidentatum, A. negundo, Ostrya knowtonii, and Pseudotsuga menziesii. The Douglas fir stands did not depart in dispersal spectra from expectation compared with the two montane groups (χ^2=1.25, p=0.26 with upland species; χ^2=0.63, p=0.43 with wetland species; Yates-corrected tests). Bird dispersed species were not more widespread than other species (average of 2.4 vs. 2.6 sites, respectively).

A strong positive correlation existed between woodiness and bird dispersal. A majority of bird dispersed species in all four groups were woody. For both montane groups, bird dispersal and woodiness were highly significantly dependent (χ^2=27.9, p«0.001 for upland species; χ^2=12.9, p<0.001 for wetland species; Yates-corrected tests). However, for Douglas fir site and total disjunct species groups, this relationship was much weaker and non-significant (χ^2=2.16, p=0.14 for Douglas fir site species; χ^2=1.99, p=0.16 for all disjunct species; Yates-corrected tests). A larger proportion of woody disjunct species were wind dispersed than in the montane data sets.

An analysis of traits among the expanded group of disjunct montane species is presented in Table 6. Woody, bird-dispersed upland species that were either clonal or could readily resprout following disturbance predominated. Traits that were rare among montane disjuncts included herbaceous habit, annuals, and selfers.

Table 4. Sample relevé data from each stand of Douglas fir, based on the technique described in Rowlands (1994). For sites with more than one relevé, data were combined and a mean importance value shown. The most important understory species is in bold type.

Species	UMC	MIC	SITE[1] FS1	FS2	SHA
[Number of relevés	4	2	1	1	2]
Acer glabum	-	-	-	-	**4**[2]
A. grandidentatum	**4**	-	-	-	-
A. negundo	-	-	1	-	-
Juniperus osteosperma	-	-	-	-	1
Ostrya knowltonii	2	-	-	-	-
Quercus gambelii	2	2	-	4	2
Pinus edulis	-	1	-	-	1
Amelanchier alnifolia	-	2	1	1	-
A. utahensis	-	2	-	-	3
Berberis fendleri	-	-	-	-	3
Chrysothamnus linifolius	-	-	-	-	-
Cornus sericea	-	**3**	-	**5**	-
Fraxinus anomala	-	-	-	2	-
Holodiscus dumosus	-	-	-	-	2
Mahonia fremontii	-	1	-	-	-
M. repens	2	-	-	-	-
Rosa woodsii	1	2	**4**	4	-
Salix lutea	-	-	-	2	-
Symphoricarpos longiflorus	-	1	-	-	-
S. cf. oreophilus	-	-	-	-	1
Toxicodendron rydbergii	2	-	-	-	-
Apocynum cannabinum	-	-	2	-	-
Aquilegia micrantha	-	-	-	1	1
Clematis ligusticifolia	-	1	-	2	-
Erigeron utahensis	1	-	-	-	-
Senecio multilobatus	-	-	1	-	-
Calamagrostis scopulorum	-	-	-	2	-
Carex rossii	1	2	-	-	2
Elymus elymoides	-	1	-	-	-
E. salinus	-	-	1	-	-
Habenaria zothecina	1	-	-	2	-
Smilacina stellata	2	-	-	2	-
Stipa lettermannii	-	2	-	-	2

[1]UMC=Upper Miller's Creek, MIC=Millard Canyon, FS1=French Spring Fork of Happy Canyon alcove 1; FS2=French Spring Fork of Happy Canyon alcove 2; SHA=Shafer Alcove.

[2]Importance values denote: 5=dominant species, abundant and quantitatively important (biomass and density); 4=subdominant, less common but still quantitatively important; 3=common but not quantitatively important; 2=uncommon, scattered, can be found after some searching, not quantitatively important; 1=rare, only one or a few individuals, very hard to find, not quantitatively important.

Table 5. Comparisons of life form and dispersal category spectra for four groups of species; (1) Douglas fir stand disjunct and wetland species, (2) an expanded set of disjunct species including data from riparian zones around Lake Powell, (3) 100 montane upland Douglas fir forest species, and (4) 100 montane riparian Douglas fir species.

	Species Group			
	(1)	(2)	(3)	(4)
Number of Species	26	30	100	100
Life Form				
Woody (tree/shrub)	15	19	45	35
Herbaceous Forb	9	7	34	40
Herbaceous Graminoid	2	4	21	25
Dispersal Category				
Bird dispersed	10	12	25	28
All other types	16	18	75	72

DISCUSSION

The Douglas fir populations in four of the five sites investigated were reproducing, as indicated by the presence of seedlings and a variety of size classes (Spence, unpublished data). Only at Shafer Alcove in Canyonlands National Park was evidence of recent reproduction lacking. All stands occurred in north facing alcoves associated with springs. It is likely that the species can only exist at such low elevations in alcoves with their cool moist microclimates and relatively low levels of sunlight. Because of these microclimatic effects, the Douglas fir stands are capable of growing and reproducing in a regionally hot and arid climate which is characterized by xeromorphic shrublands and pinyon-juniper woodlands. Cole (1985) presented a model of vegetation inertia from his work in the Grand Canyon, in which species can persist for several hundred years or more at a site following climate change, even though they no longer reproduce. This occurs primarily because local microclimates are favorable for survival, and often also because local soil conditions have been modified by existing vegetation. The Shafer Alcove stand may be moving into this phase as recruitment seems to have ceased at this site. However, the remaining four stands consist of dynamic assemblages with at least intermittent recruitment. As long as critical climatic thresholds, such as adequate moisture for seedlings establishment, are not exceeded by climate change, these stands will continue to occupy the alcoves and not be replaced by arid species.

The understories of these populations of Douglas fir consisted primarily of common and widespread montane species, including many characteristic of conifer forests on the Colorado Plateau. Typical of this group are Acer glabrum, A. grandidentatum, and Rosa woodsii in riparian settings, and Carex rossii and Mahonia repens in drier sites. The joint occurrence of common high elevation associates which are not easily dispersed, such as Douglas fir and Carex rossii, suggests that these species assemblages are not the result of independent dispersal events by birds into the same site. Other species that are unlikely to have dispersed to the alcoves include Acer glabrum and A. grandidentatum. The fruits of these species are relatively heavy samaras, and the wings function primarily to disperse the

Table 6. Predominant morphological and reproductive traits among the group of 30 montane disjunct species found in isolated Douglas fir stands and riparian woodlands on the central Colorado Plateau. Thirty species are represented. The ten most common species are presented, based on data in Spence (1995) and the present work.

TRAIT	PREVALENCE (% OF 30 SPP.)
1. CLONAL OR READILY RESPROUTS	73%
2. WOODINESS (TREE/SHRUB)	63%
3. BIRD DISPERSED	62%
4. UPLAND/DRY SITE HABITAT	60%
5. INSECT POLLINATED	57%
6. WETLAND/RIPARIAN HABITAT	40%
7. WIND POLLINATED	30%
8. PERENNIAL FORBS	23%
9. GRAMINOIDS	13%
10. SELFERS	3%
11. ANNUALS	3%

MOST COMMON SPECIES

1. *Smilacina stellata*
2. *Calamagrostis scopulorum*
3. *Rosa woodsii*
4. *Mahonia repens*
5. *Betula occidentalis*
6. *Habenaria zothecina*
7. *Carex rossii*
8. *Pseudotsuga menziesii*
9. *Acer grandidentatum*
10. *Amalanchier alnifolia*

fruits away from the parent's canopy influence. Seed-eating birds, such as members of the Fringillidae, eat the seeds of Acer, but they actually consume the seeds rather than allowing them to pass through their guts. The dispersal hypothesis is not supported by the χ^2 results between dispersal category and growth form. Woody species were primarily bird dispersed in the two montane data sets. However, the relationship between bird dispersal and woodiness in the montane disjuncts in the Douglas fir stands was much weaker. Proportionally, more species in these stands were wind dispersed, a pattern opposite to that in higher elevation forests. The presence of the two ferns, Cystopteris fragilis and Adiantum capillus-veneris, however, is probably best explained by long distance dispersal of spores by wind.

The alternative hypothesis is that these stands represent relict populations from the late Wisconsin or early Holocene, ca. 10,000–12,000 yrs BP. Several lines of evidence suggest that these stands are relictual. Fossils of many of these species have been found in alcove sites throughout the region, with associated radiocarbon dates ranging from 8,000 yrs to 15,000 yrs BP. In the Willow and Forty Mile gulches of the Escalante drainage, Withers and Mead (1993) reported Abies sp., Acer grandidentatum, Betula occidentalis, Juniperus scopulorum, Picea sp., Pseudotsuga menziesii, Quercus gambelii, Ribes cf. cereum, Rosa woodsii, and Smilacina sp. from a variety of alcove sites. All of these except the montane conifers currently survive in scattered populations in nearby Cow Canyon, as well as upper Miller's Creek, only a few km to the east. A pack rat midden from the alcove harboring the Douglas fir in upper Miller's Creek, dated at 13,000 radiocarbon yrs, has Douglas fir as well as a variety of other species (Sharpe and Spence, unpublished data).

If the assumption that these stands are relictual is correct, several conclusions can be drawn. First, Douglas fir is apparently capable of surviving for thousands of years in small populations in cool microclimates within arid to semi-arid climates. This long term presence also permits the survival of understory species that probably could not exist on their own. These isolated stands could function as refugia out of which species migrate during periods of climate change. The sometimes rapid appearance of species in the paleoecological record may be explained by expansion out of such local refugia rather than migration into an area from outside. Another conclusion is that the water sources (springs) in these alcoves and the regional climate have not varied enough in the past 10,000 years to eliminate these stands. Withers and Mead (1993) suggested that climate variation in the last 10,000 years in the Escalante drainage has been relatively minor compared to previous changes.

Extinction of montane species since the late Wisconsin may not have been a random process. A small but significant group of species occurs at all or most site alcoves, and in particular the three stands in the Orange Cliffs area show strongly positive relationships. Random extinction (or dispersal) would be more likely to generate a pattern where floristic relationships were within random expectations. These results are tentative, however, because of the small sample sizes. An expansion of the data set by including additional stands would be necessary to strengthen this conclusion.

The analysis of the traits of the montane disjuncts indicates that some features are much more prevalent than expected. Woodiness, ability to resprout or persist vegetatively, and insect pollination are common. Most of the species have relatively long generation times, in the case of Douglas fir several hundred years. In other species, such as Cornus sericea, clonal persistence may also confer longevity. Further research into physiological and genetic characteristics of those species that have persisted, as well as species that existed in the alcoves in the Wisconsin but subsequently became extinct (e.g., Juniperus scopulorum, Picea pungens, and Pinus flexilis) would provide useful data on the extinction process.

More tests of both the relict and dispersal hypotheses are clearly needed. A variety of fruit-eating birds migrate through the Colorado Plateau, including pigeons, thrushes, and waxwings. Also, local residents, in particular Scrub Jays, also eat fruit. Occasional irruptions of Clark's Nutcrackers occur downslope into the pinyon-juniper woodlands during heavy pine crop years. The extent to which these birds, as well as Pinyon Jays, collect and cache Douglas fir is not known, although Douglas fir is probably not important to specialized seed-caching birds (Tomback and Linhart 1990). It remains possible that these bird species in fact do disperse seeds of montane plant species as they migrate. Genetic tests, particularly of Douglas fir and the Acer species would provide useful data on population genetic diversity. Such work could provide a test of the relict hypothesis. Finally, searches for pack rat middens in or near the alcoves would provide valuable data on the past presence of species, as well as species that may have originally existed but have become locally extinct.

These isolated stands of Douglas fir are valuable resources for Quaternary research.

Detailed studies can provide important data on extinction and persistence of populations and the effects of climate changes. The establishment of long-term monitoring programs should be done to monitor possible changes in climate that may affect both the stands as well as other plant species of concern. Because of their vulnerability to disturbances, such as fire, they should be managed as protected sites by the various land management agencies. Appropriate protection would include designation as protected natural areas or research natural areas (National Park Service, U.S. Forest Service), or areas of critical environmental concern (Bureau of Land Management).

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Session III: Climate Change and Past Cultures

DENDROCLIMATIC RECONSTRUCTIONS FOR THE SOUTHERN COLORADO PLATEAU

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Keywords: *dendrochronology, dendroclimatology, paleoenvironment, Colorado Plateau, cultural adaptation*

ABSTRACT

A geographical network of climate sensitive tree-ring chronologies consisting of 25 archaeological sequences and two bristlecone pine series provides the basis for high resolution reconstructions of low and high frequency climatic variability on the southern Colorado Plateau over the last 1,500 years. Qualitative and quantitative dendroclimatic analyses of these data produce annual retrodictions of yearly and seasonal precipitation and summer Palmer Drought Severity Indices for each station and reconstructions of regional scale patterns in climatic variability. These reconstructions provide detailed information on climatic fluctuations that affected biotic and human populations as well as long-term baseline data for evaluating present-day climate and estimating future climatic trends. When integrated with other measures of past environmental variability, these reconstructions specify periods of favorable and unfavorable environmental conditions that would have affected past human populations of the region. The severest degradation, which occurred between A.D. 1250 and 1450, probably was causally related to numerous cultural changes that occurred at the end of the 13th century including the Anasazi abandonment of the Four Corners area. Projecting environmental patterns that characterized the last two millennia into the future indicates potential hazards to long term uranium mill waste disposal and containment and the potential and limitations of environmental restoration.

INTRODUCTION

Dendroclimatic research in general and on the Colorado Plateau in particular began early in the 20th century with the work of Andrew Ellicott Douglass, an astronomer at the Lowell Observatory in Flagstaff, Arizona, who was investigating relationships between solar activity and terrestrial climate. Lacking weather data long enough to establish climatic cycles comparable to the known 22-year sunspot cycle, he turned to the annual rings of trees as possible climatic records and invented the science of dendrochronology (Douglass 1909, 1914, 1919). Dendrochronology (Bannister 1963:161) employs the annual growth rings of trees as measurements of time and a means of dating past events (Dean 1978a) and as proxy records of past environmental conditions and changes (Fritts 1976). The first aspect of dendrochronology endows Southwestern archaeology with the finest prehistoric chronological controls in the world (Dean 1978b, 1986); however, our primary concern here is the second aspect, the reconstruction of past environmental variability.

Douglass first established a quantitative relationship between tree growth and climate in 1914 when he showed a strong positive correlation between ring width and the precipitation of the preceding winter (Douglass 1914). This discovery was developed into the subdiscipline of dendroclimatology, which is concerned with the relationships between tree growth and various external factors and with using variability in ring morphology to estimate past fluctuations in these environmental factors. Douglass' insistence on the uncompromising application of rigorous procedures and standards of tree-ring dating (Douglass 1946) established a firm conceptual and analytical foundation for dendroclimatic reconstruction. Although much of Douglass' subsequent work was focused on the cyclic information in tree-ring series, his colleagues and successors maintained and refined the discipline.

Dendroclimatic research was significantly advanced by Douglass' protégé, Edmund Schulman, who made tremendous strides with comparatively rudimentary analytical techniques. Schulman's scientific vision was enormous, but his efforts were impeded by the inadequacies of the available analytical methods and equipment. He was, for example, forced to analyze vast quantities of data and perform complex statistical operations with hand cranked calculators. His crowning achievement (Schulman 1956) was the publication of Dendroclimatic Changes in Semiarid America, which incorporated many tree-ring chronologies into an analysis of past climatic variability across western North America. Schulman's painstaking work established high standards for dendroclimatic research and set the stage for the great leap in dendroclimatology that occurred only a few years after his untimely death in 1958.

In the 1960s, Harold C. Fritts (1976), his colleagues, and students employed biological expertise, sophisticated multivariate statistical techniques, and computers capable of handling large quantities of data to revolutionize dendroclimatology. They developed and perfected current standards and techniques, which involve the simultaneous analysis of scores of tree-ring and environmental variables over many centuries. These procedures established consistent relationships between tree growth and environmental factors that are used to produce both qualitative and quantitative environmental reconstructions from tree-ring chronologies.

The research covered in this paper applies modern techniques of dendroclimatic analysis to long tree-ring chronologies that combine ring records from both living trees and archaeological samples in the Southwest. The Laboratory of Tree-Ring Research's "Southwest Paleoclimate Project" is a long term dendroclimatic study that grew out of the "Synthesis Project," a National Science Foundation-sponsored reanalysis of the Laboratory's Southwestern archaeological tree-ring collections undertaken between 1962 and 1975 (Robinson et al. 1975:1–2). Among other things, the Synthesis Project produced a large number of measured archaeological tree-ring samples suitable for dendroclimatic analysis. Subsequent grants from the National Park Service, the Southwestern Parks and Monuments Association, and the Department of Defense Advanced Research Projects Agency underwrote the collection and processing of living-tree samples from the region, the construction of 25 climate-sensitive composite ring chronologies composed of archaeological and living-tree samples (Dean and Robinson 1978), and the reconstruction of relative climatic variability in the Southwest from A.D. 680 to 1970 (Dean and Robinson 1977). During the last three years, additional NSF support has allowed the Southwest Paleoclimate Project to produce quantitative reconstructions of annual and seasonal precipitation and temperature, drought, and streamflow for the region.

DENDROCLIMATIC ANALYSIS

Dendroclimatic analysis is extremely complicated. Fortunately, the relevant assumptions, principles, and procedures have been described in detail elsewhere (Fritts 1976; Graybill 1982;

Rose et al. 1981), and they need be only summarized here.

In general, two types of dendroclimatic reconstruction are possible (Dean 1988b). Qualitative reconstructions use tree-ring chronologies as direct measures of relative variability in past climate. In the Southwest, the strong positive correlation between tree growth and precipitation (Fritts 1974) establishes such reconstructions as accurate indicators of relative deviation from average annual rainfall. Quantitative reconstructions, on the other hand, employ mathematical expressions of the relationships between tree growth and specific environmental variables—precipitation, temperature, air pressure, drought, streamflow, crop yields, etc.—to statistically estimate annual and seasonal values for appropriate measures of these variables, such as inches of precipitation, degrees of temperature, millibars of pressure, Palmer Drought Severity Indices (PDSI), acre-feet of runoff, and bushels or pounds per acre of various crops.

Two kinds of data, tree-ring and environmental, are involved in quantitative dendroclimatic reconstruction. Usually, the former consist of long tree-ring chronologies produced by averaging standardized ring-width indices from hundreds of samples from trees that grew in a fairly restricted geographical area. Such chronologies can consist entirely of samples from living trees, from living trees and deadwood remnants, or from living trees and archaeological and/or geological wood. Whatever a chronology's composition, it includes only samples that have been carefully screened against criteria known to characterize great sensitivity to climatic or other environmental factors. These criteria include growth-site characteristics for living trees (Fritts 1976:17–19; Fritts et al. 1965a) and several morphological and statistical characteristics of the individual sample ring series (Fritts 1976:28–34; Fritts and Shatz 1975; Rose et al. 1981:11–15).

The environmental data consist of primary or secondary records of the relevant variables from locations throughout the study region. Most commonly, meteorological records supply primary data on factors such as precipitation, temperature, and frost-free period or data used to calculate derivative measures such as PDSI. Other environmental data, such as records of atmospheric pressure, streamflow, and crop production, are less commonly used.

Both the tree-ring and environmental data sets are rigorously tested for statistical stability, representativeness, and suitability for statistical analysis before they are used in dendroclimatic reconstruction (Fritts 1976:246–311; Rose et al. 1981:11–47). Tree-ring data that do not meet the established criteria are rejected; environmental data that fail to conform are either rejected or, in rare instances, corrected.

Once the tree-ring and environmental data have been evaluated, they are incorporated into the calibration process (Fritts 1976:312–375; Rose et al. 1981:49–78). Calibration involves the derivation of equations that express the relationship between a tree-ring chronology and an environmental record for a purposefully or randomly selected part of the period over which the two records overlap. In climatic calibration, response functions characterize the relationships between ring widths and monthly rainfall and temperature and indicate those climatic variables that are potentially reconstructible. Next, transfer functions are developed from the response functions to estimate values of the reconstructible climatic variables from the ring-width data. Alternatively, in areas (such as the Southwest) where there is a strong relationship between tree growth and climate, regression analysis can be used to directly reconstruct past climate from tree-ring widths.

Completion of the calibration process initiates the verification stage of the analysis (Fritts 1976:376–433; Rose et al. 1981:79–89). The reconstructions derived from the application of the transfer functions are first evaluated with a variety of tests designed to characterize their statistical properties and internal consistency. Second, a battery of statistical tests is used to assess the fit between reconstructed values and those segments of the instrumented climatic data that were withheld from the calibration process. Reconstructions that do not exhibit acceptable statistical properties or that do not correlate sufficiently well with the verification climatic data sets are rejected as suitable for further retrodiction.

The equations for the reconstructions that survived verification are used to retrodict the appropriate environmental values as far back in time as the relevant ring chronologies allow. To give a hypothetical example, this process could produce quantitative estimates of annual values of tree-year (August of the year prior to the growth of a particular ring through July of the current growth year), prior winter, and current spring precipitation, average current summer temperature, current July PDSI, and the annual flow of a particular stream for the last 1000 years. Such reconstructions provide detailed information on past environmental variability that is invaluable for assessing environmental effects on past natural and cultural systems and that provide an empirical baseline for predicting future environmental variations.

Qualitative and quantitative reconstructions of the types outlined above have been made for various localities on the southern Colorado Plateau. Relevant qualitative reconstructions include those of Fritts (1965) for western North America; Fritts, Smith, and Stokes (1965b) for Mesa Verde; and Dean and Robinson (1977) for the Southwest. Quantitative dendroclimatic retrodictions pertinent to the region include Stockton's (1975) reconstruction of Colorado River streamflow, Rose et al's. (1981, 1982) climatic reconstructions for the Santa Fe and Four Corners areas, Burns' (1983) crop yield and Van West's (1990) PDSI and crop yield reconstructions for southwestern Colorado, and Dean's (1986) and Lebo's (1991) precipitation reconstructions for Black Mesa. Several of these retrodictions have been integrated into large scale syntheses that attempt to characterize past climatic variability across the entire region (Dean 1993; Dean et al. 1985; Euler et al. 1979; Plog et al. 1988).

DENDROCLIMATIC RECONSTRUCTION IN THE FOUR CORNERS

The tree-ring data used in the Southwest Paleoclimate study comprise a spatial grid of 27 long tree-ring chronologies that extends from the Grand Canyon on the west to the Pecos River on the east and from central Utah south to the Gila River (Dean 1988b, Figure 5.3). Twenty-five of these chronologies are composed of archaeological and living-tree samples. The other two are multimillennial bristlecone pine series from Mammoth Creek and Wild Horse Ridge, Utah, on the northwestern margin of the grid. The climate data include weather service divisional summaries for Utah, Colorado, Arizona, and New Mexico and records for individual weather stations near the tree-ring chronologies. Variables used include total precipitation for the "tree year" (previous August through current July) and various seasons, annually and seasonally averaged temperatures, Palmer Drought Severity Indices for June and July, total annual streamflow for adequately gauged streams, and crop yield data from southwestern Colorado.

The qualitative reconstructions consist of tree-growth departures (Dean and Robinson 1977; Fritts 1965) in standard deviation units for each of the 27 chronology stations averaged by decade. The departure values indicate relative variability in annual rainfall, with values outside the ± 1.1 range considered to be significantly above or below the long term mean with respect to potential favorable or adverse impacts on plant and animal populations and human adaptive behavior (Dean 1988b). Departure sequences for each station represent yearly and decadal fluctuations in annual weather (rainfall and temperature) at the locality represented by that station.

Regional scale behavior of relative climatic variability across the study area is represented by contouring the array of station departure values for each decade. Temporal aspects of regional climatic variability are revealed by arranging the decade maps in order for the period from A.D. 680 to 1970 (Dean and Robinson 1977). The sequence begins at A.D. 680 because too few chronologies extend inside that date to make reliable contouring feasible. The utility of these maps for understanding past climatic behavior in the Southwest is exemplified by Figures 1 through 4, which show the northeast to southwest progression of the "Great Drought" of A.D. 1276–1299 across the region. In the A.D. 1270 to 1279 decade (Figure 1), the beginnings of the drought are evident in the negative departures in the northwestern half of the region, while the rest of the region is characterized mainly by positive values. During the next decade (Figure 2) extremely dry conditions expanded to encompass the entire region except for the area around Flagstaff, Arizona. By the 1290–1299 decade (Figure 3), positive departures in the Rio Grande Valley interrupt the otherwise negative values throughout the region. A decade later (Figure 4), widespread high positive values signal the end of the Great Drought. Long-term changes in regional climatic patterns of the sort seen in the Great Drought example can be traced through the entire 1300-year sequence of departure maps.

Quantitative dendroclimatic reconstructions have been made for a wide range of climatic variables. Tree-year and seasonal precipitation

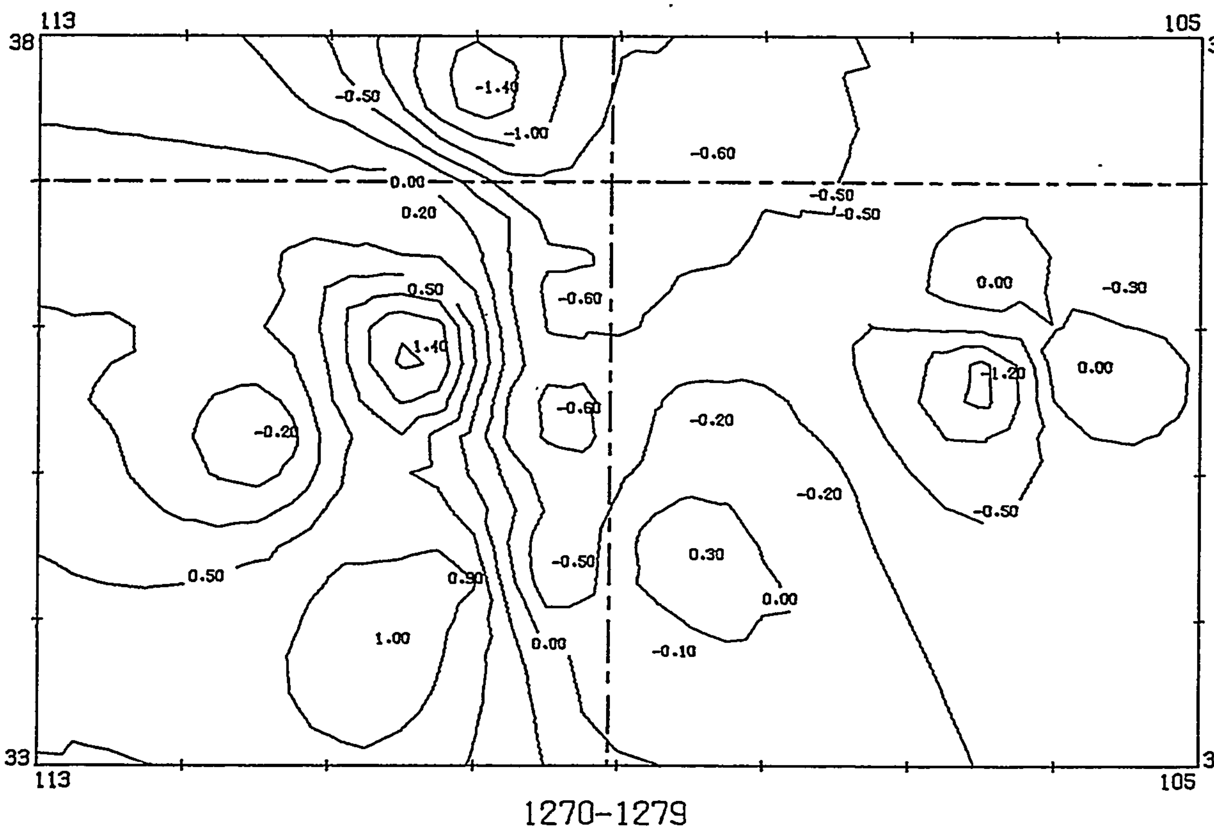


Figure 1. Contour map of Southwestern tree-growth departures for the A.D. 1270–1279 period.

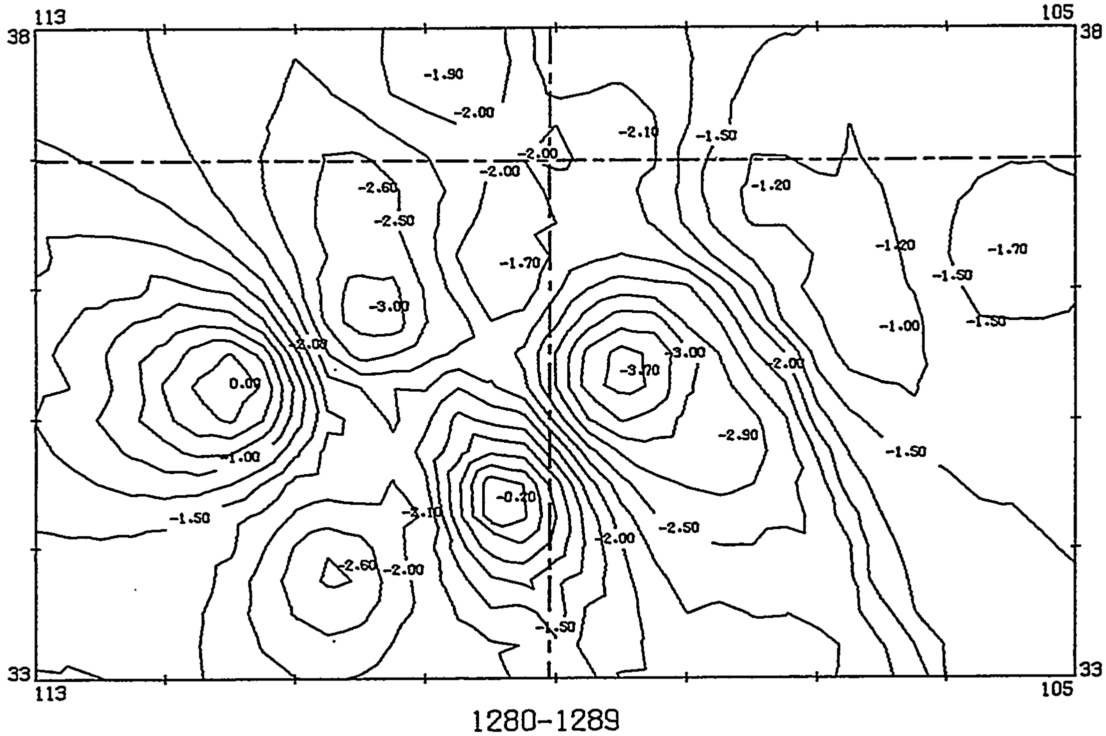


Figure 2. Contour map of Southwestern tree-growth departures for the A.D. 1280–1289 period.

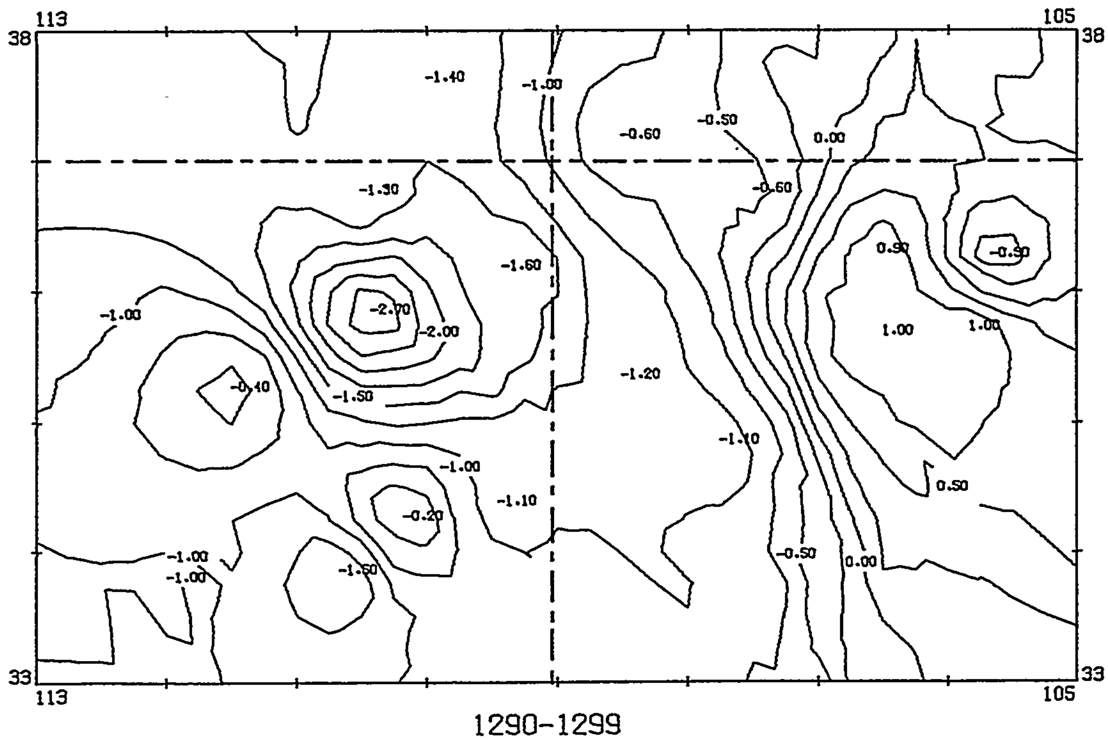


Figure 3. Contour map of Southwestern tree-growth departures for the A.D. 1290–1299 period.

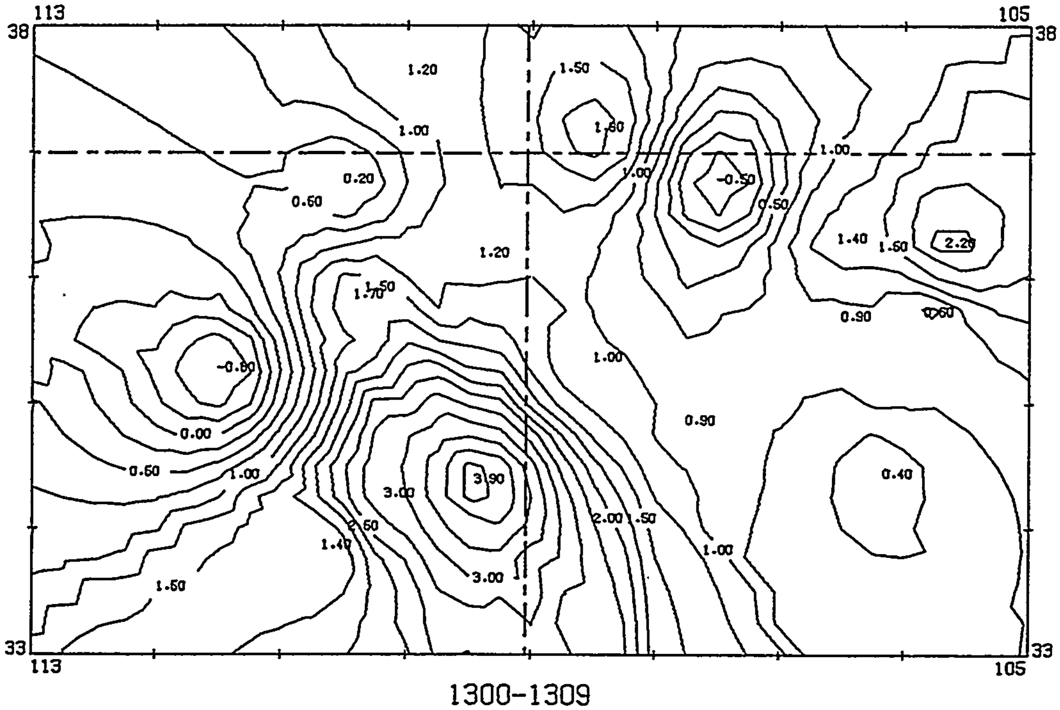


Figure 4. Contour map of Southwestern tree-growth departures for the A.D. 1300–1309 period.

in inches per year has been calculated for each of the 27 chronology stations. Similarly, annual June and July PDSI values have been estimated for each station. Streamflow reconstructions in millions of acre-feet per year, similar to that done by Graybill (1989) for the Salt and Verde Rivers in southern Arizona, have been done for the Colorado River (Stockton 1975) and are contemplated for other Plateau streams with acceptable gauge records. Annual crop yield values for corn and beans have been estimated for southwestern Colorado, the only area on the southern Colorado Plateau with usable modern crop production records (Burns 1983; Van West 1990). All these reconstructions are statistically significant estimates of past amplitude fluctuations in the relevant climate measures. These estimates can be presented as annual values, averaged over longer periods, or smoothed to show longer trends.

Both the qualitative and quantitative reconstructions portray important aspects of past climatic variability in addition to simple amplitude (wet vs. dry) fluctuations. Temporal variability, the rate of change from high to low values, varies systematically through time. During some periods, fluctuations from maximum to minimum values are rapid, often occurring from one decade to the next. At other times the transition is more gradual with the change occurring over several decades. The hatched zones in Figure 10D indicate periods of high temporal variability interspersed among intervals characterized by more temporal persistence (low temporal variability).

Related to temporal variability is the recurrence interval of high or low extreme values. There appear to be fairly regular periodicities in the incidence of extremes in many local reconstructions. This phenomenon, however, has yet to be systematically investigated and its amplitude range, spatial characteristics, and periodic structure are not well known (Graybill 1991). Other poorly understood variables are the variance structure of the regional network (Dean 1988b, Table 5.1) and subdivisions of the regional array (Dean, in press), although both these attributes fluctuate during the last 1300 years.

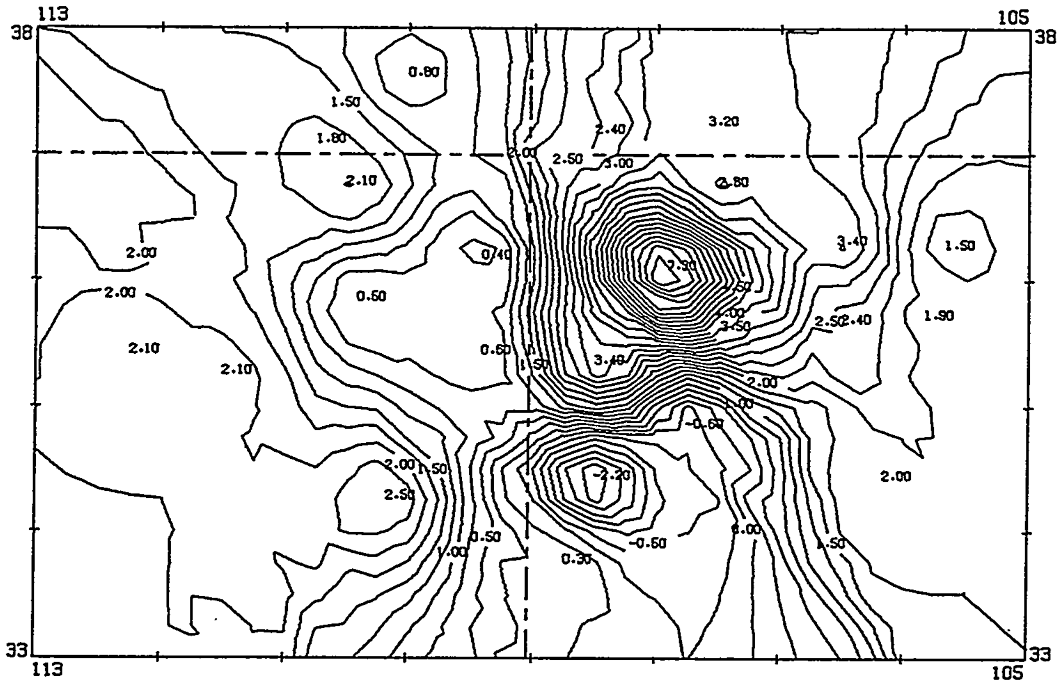
Finally, there is considerable climatic variability across space. Some periods are characterized by high spatial variability (Figure 5), while in others a great deal of spatial uniformity prevailed (Figure 6). Figure 10E, a plot of the standard deviations of the station departures for each decade, shows that spatial variability was low (that is, conditions were similar throughout the region) in the A.D. 700 to 1000, 1150 to 1300, and 1650 to 1900 intervals and high (conditions varied across the region) during the A.D. 100 to 1150, 1300 to 1650, and 1900 to 1970 periods.

Additional aspects of the spatial behavior of climate across the Southwest during the last 1500 years are indicated by recent multivariate analyses. In order to illuminate the spatial structure of Southwestern climate, principal components analysis (PCA) was employed to investigate the geographic patterning of covariation among the tree-ring chronologies. Principal components analysis partitions the chronologies into statistically independent subgroups that exhibit similar patterns of variation (the principal components). Drawing boundaries around the chronologies that contribute heavily to individual principal components produces fairly coherent and logical patterns.

Analysis of the entire study period, A.D. 966 to 1988, revealed two spatially discrete principal components (Figure 7). The first component includes stations in the northwestern part of the region and accounts for approximately 60% of the total variance in the network. Principal Component 2 includes stations in the southeastern part of the region and accounts for about 10% of the variance. This general configuration bears an uncanny resemblance to the modern spatial distribution of seasonal precipitation in the Southwest during the last 70 years (Dean 1988b, Figure 5.1). In the south and east, precipitation exhibits a unimodal, summer dominant pattern, while to the north and west, a bimodal distribution with both summer and winter maxima prevails. These areas are separated by a sinuous boundary zone that runs eastward from the southwestern corner of Arizona, turns northward at the New Mexico border, loops back into Arizona on the Colorado Plateau, curves back to parallel the Colorado—New Mexico border, and ends in the mountains north of Santa Fe. Given the striking resemblance between the climatic configuration and the PCA pattern, the PCA dichotomy probably reflects the long-term persistence of the geographic division between summer-dominant rainfall in the southeast and summer-winter precipitation pattern in the northwest.

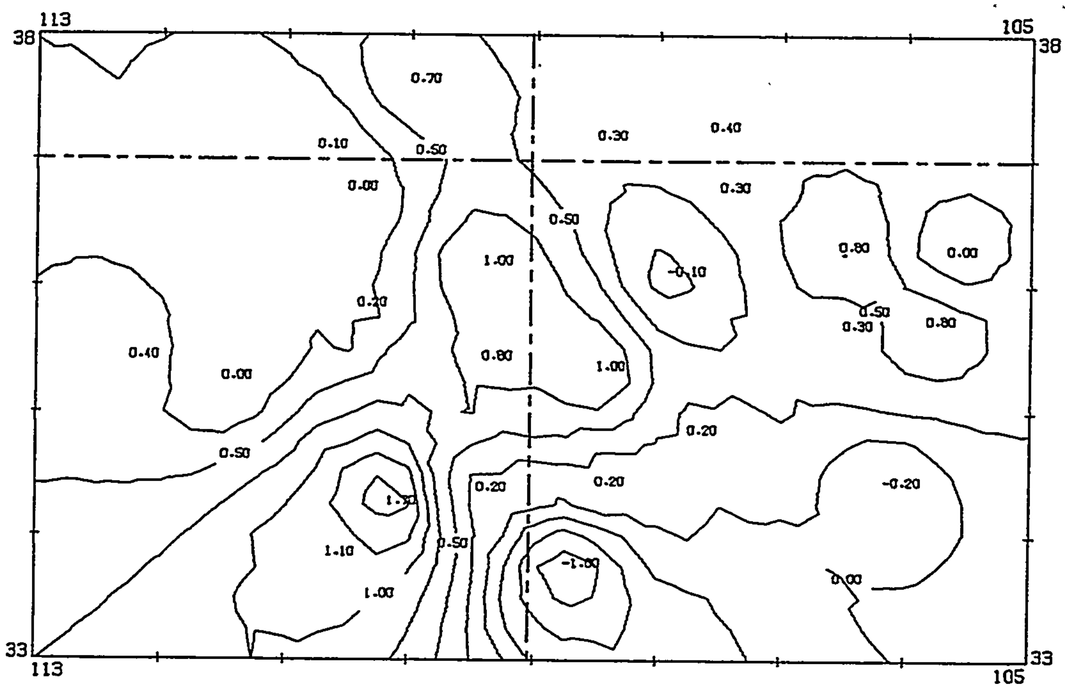
Temporal aspects of this regional spatial pattern are revealed by principal components analyses of each 100-year period from 539 to 1988 overlapped by fifty years. By and large, the bimodal PCA pattern persists throughout the period of record. The A.D. 739–838 period (Figure 8) exemplifies the general pattern. A couple of things are evident when this map is compared to the 966–1988 map (Figure 7). The most obvious is that different combinations of stations are included in each component, a reflection of the fact that the boundary between the two zones moves back and forth in space over time. Examination of the entire series of maps shows that while the boundary does indeed fluctuate in time, it always maintains its general position and configuration.

The PCA also revealed that the general pattern was not uninterrupted. During a 200-year period, the long-term pattern breaks down completely. The A.D. 1339–1438 interval (Figure 9) typifies the period from about 1250 to 1450 when a totally aberrant pattern prevailed. The A.D. 1339–1438 interval exhibits four rather than two major principal components, and some 100-year segments of the two century period have as many as six



1610–1619

Figure 5. Contour map of Southwestern tree-growth departures for the A.D. 1610–1619 decade showing high spatial variability in climate.



1860–1869

Figure 6. Contour map of Southwestern tree-growth departures for the A.D. 1860–1869 decade showing low spatial variability in climate.

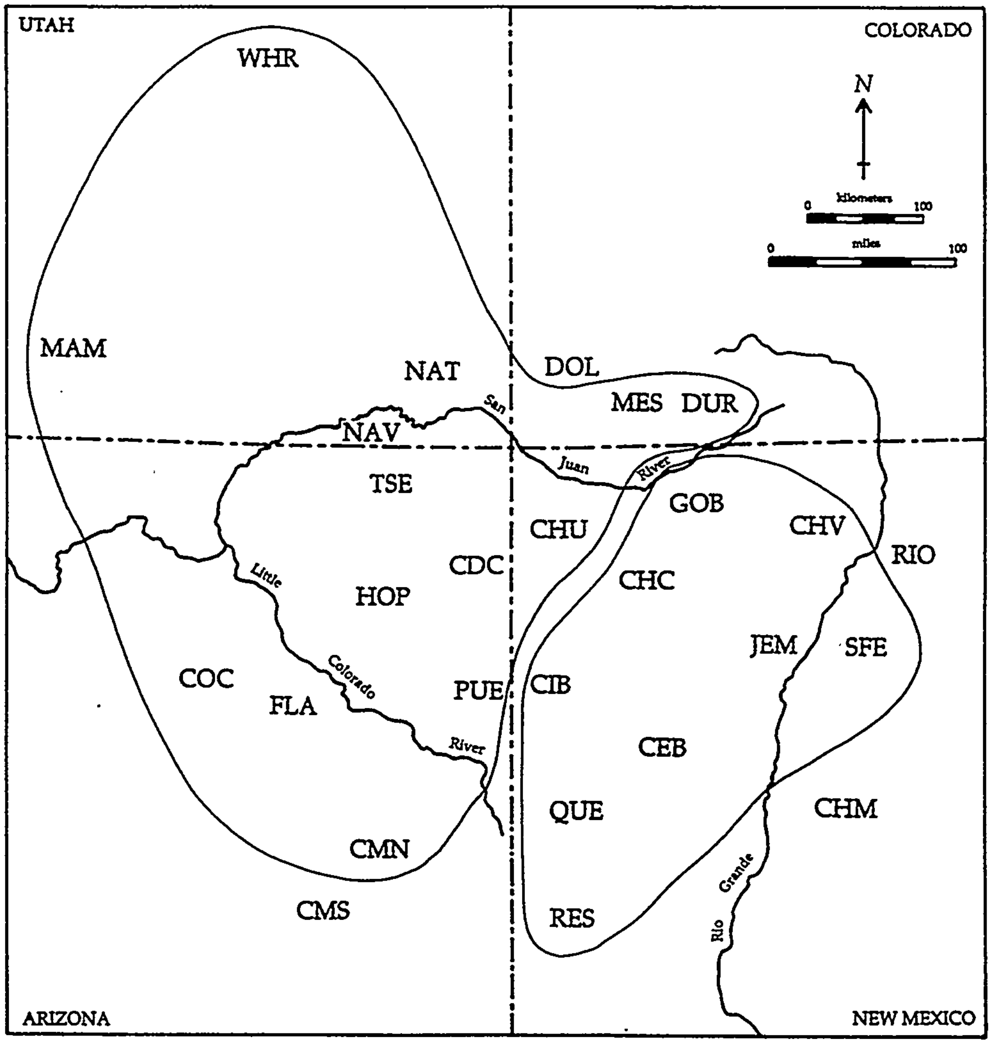


Figure 7. Principal components of Southwestern tree growth (climate) for the A.D. 966–1988 period.

components. Unlike the patterns of other periods, this chaotic configuration makes little sense in terms of modern climate. The only stable characteristic of this period is the persistence of the southeastern component, which indicates that most of the disruption of the long term pattern occurred in the northwestern area.

These results specify a major climatic disruption that would have had major impact on the Colorado Plateau. For two centuries a fairly simple, long-term, stable pattern was interrupted by a complex, chaotic configuration that represents an unprecedented change in conditions to which the human and biotic populations of the region had become accustomed. The effects of this disruption obviously were greatest in the northwestern part of the region, basically, the Colorado Plateau. Just the change from a persistent stable pattern to an unstable one would have had important adaptive repercussions. The probable breakdown of the bimodal seasonal distribution of precipitation would have had even more specific consequences for the farming populations of the region, especially when

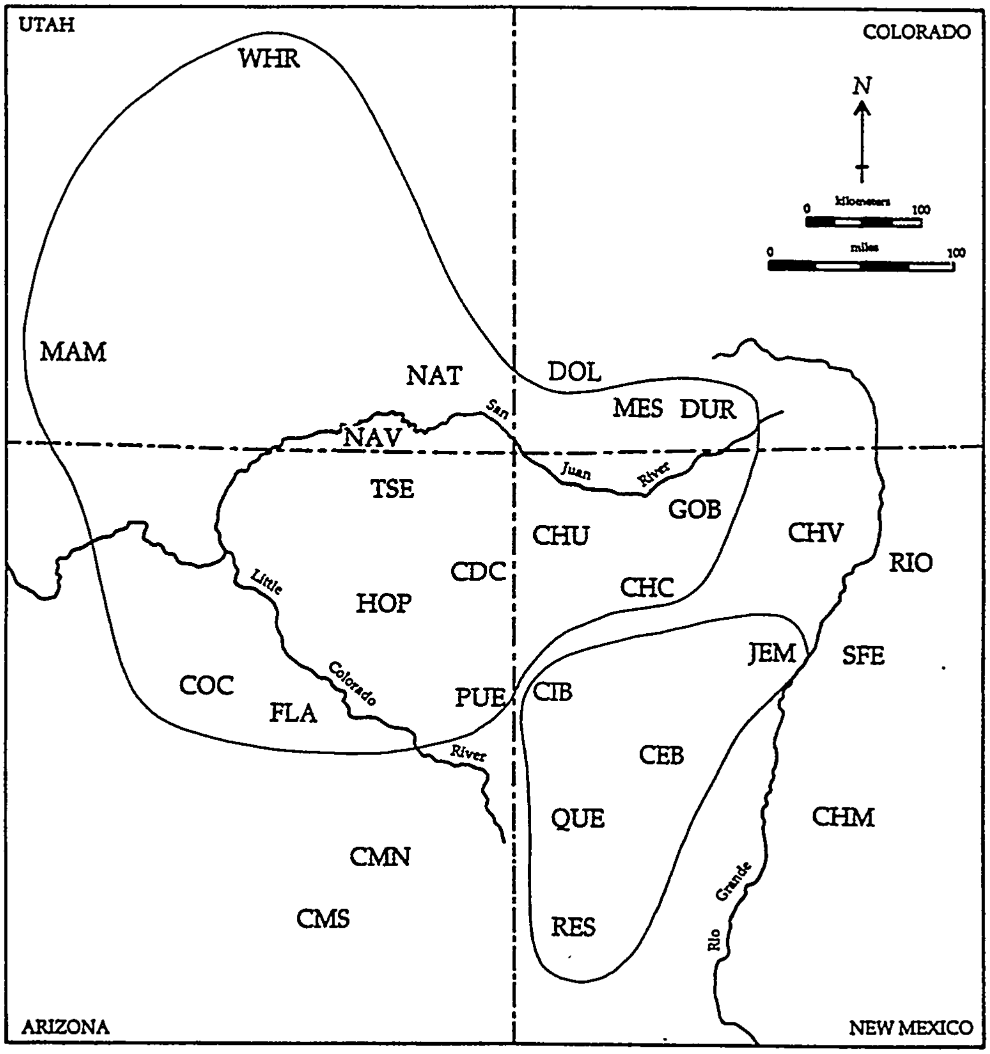


Figure 8. Principal components of Southwestern tree growth (climate) for the A.D. 739–838 period.

combined with other environmental changes that characterized this period.

Recently, dendrochronology has allowed the reconstruction of another environmental variable that, though not climatic, is closely related to both climate and human activity. Trees that were damaged but not killed by wildfires often preserve in the scars associated with their rings records of fires that occurred in their lifetimes. Dating of these scars provides detailed histories of the timing and extent of fires in affected areas (Swetnam and Dieterich 1985). Obviously, forest fires could have influenced the plant and animal communities and the human inhabitants of the affected localities. As forest managers well know, forest fires are related to the weather, and a relationship between fire frequencies in the western U.S. and the El Niño-Southern Oscillation (ENSO) has been established (Swetnam and Betancourt 1990). Equally pertinent are relationships with human behavior. There is evidence that prehistoric and historic populations of the Colorado Plateau intentionally started fires either to clear land (Kohler and Matthews 1988) or to eliminate underbrush (Sullivan 1982). Alternatively, livestock

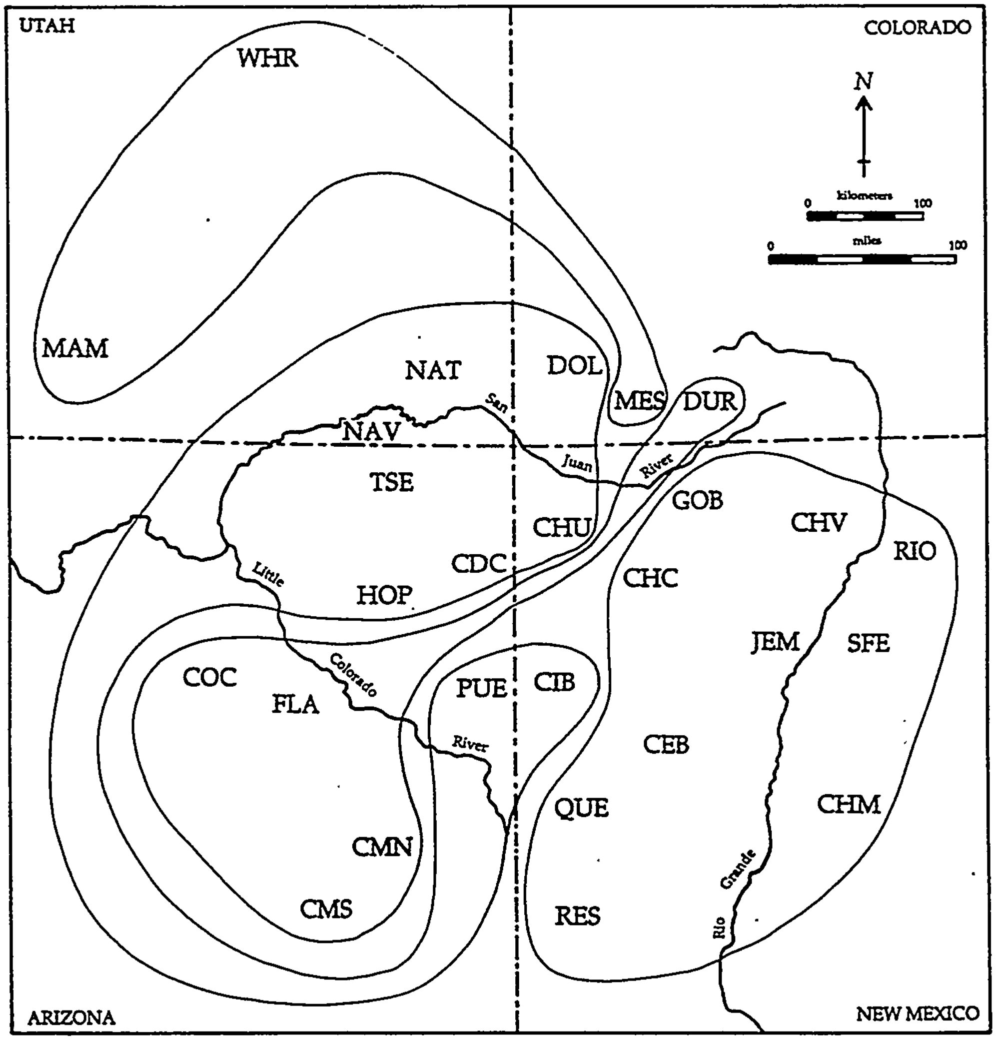


Figure 9. Principal components of Southwestern tree growth (climate) for the A.D. 1339–1438 period.

grazing and fire suppression during the historic period substantially reduced the frequency and increased the severity of forest fires. As yet, no Southwestern fire history reaches far enough into the past to illuminate the relationships of forest fires with prehistoric populations. Ongoing research, however, holds considerable promise for extending these records farther back in time.

COMPARISON WITH OTHER PALEOENVIRONMENTAL RECONSTRUCTIONS

Before the various aspects of climatic variability indicated by tree rings can be related to human behavior, they must be integrated with information derived from other paleoenvironmental indicators (Dean 1988b). Because different environmental factors present different adaptive opportunities and problems for human groups and because the effects of each factor are mitigated or amplified by the others, it is necessary to relate the dendroclimatic reconstructions to paleoenvironmental measures that record other environmental conditions and are sensitive to different spatial and temporal parameters. Other relevant indicators of past environmental variability include stratigraphic and geomorphological analysis of alluvial and colluvial deposits, palynological analyses of geological and archaeological contexts, packrat midden analysis, and archaeobotanical and zooarchaeological studies. On the southern Colorado Plateau, these disparate paleoenvironmental reconstructions are integrated through independent, high-resolution chronological control based on ceramic, radiocarbon, and tree-ring dating of stratigraphic sequences, packrat middens, and archaeological sites and on the intrinsic chronological accuracy of the dendroclimatic reconstructions (Dean 1988b). Figure 10 allows the visual comparison of fluvial, pollen, and tree-ring reconstructions on the southern Colorado Plateau.

To understand the relationships among the various paleoenvironmental reconstructions and their relevance to human behavior, environmental variability is categorized by the frequency ranges to which the different natural processes respond and to which various paleoenvironmental techniques are sensitive. One human generation, 25 years, is arbitrarily chosen as the reference for partitioning the range of variability into three categories (Dean 1984, 1988a).

Stable aspects of the past environment are those that have not changed appreciably over the length of the study period, in the case of dendroclimatic reconstruction the last 2,000 years. An important attribute of stable elements is that their present states are valid indicators of past conditions during the last two millennia. Among these features of the Colorado Plateau are climate type, bedrock geology, topography, and the elevational zonation of vegetation communities.

Low frequency environmental variability is that due to natural processes with periodicities greater than or equal to 25 years. Because these factors vary at rates shorter than the study period, they must be reconstructed. Important low frequency factors are the rise and fall of alluvial water tables (Figure 10B) and the deposition and erosion of sediments along drainages (Figure 10A), which are crucial to floodplain farming (Cooley 1962; Eddy 1964; Hack 1942; Hall 1977; Karlstrom 1988; Lipe and Matson 1975). Other low frequency variations involve elevational changes in the boundaries of vegetation zones and in the composition of plant communities (Hevly 1988; Petersen 1988). Palynological reconstructions of these variables reveal fluctuations in the effective moisture available to plants (Figure 10C). Climatic variations with frequencies longer than 25 years generally are not reconstructible by dendroclimatology, which is relatively insensitive to low frequency fluctuations. Recent progress along these lines, however, has been made through the analysis of a chronology from the El Malpais National Monument constructed of extremely long individual sample components. This preliminary reconstruction of low frequency climatic variability over the last 2,000 years (Grissino-Mayer, in press) bears an uncanny resemblance to Karlstrom's (1988) hydrologic curve (Figure 10B).

High frequency environmental variability is caused by natural processes with periods less than 25 years long. Basically, this is climate, which varies hourly, daily, seasonally, annually, and at a nearly continuous range of longer wavelengths. High frequency variability must be reconstructed. The most obvious reconstructive technique is dendroclimatology, which is sensitive to seasonal, annual, and longer variations up to about a century (Dean 1988b). High resolution pollen studies also reflect high frequency variability (Hevly 1988) with results quite similar to the tree-ring reconstructions.

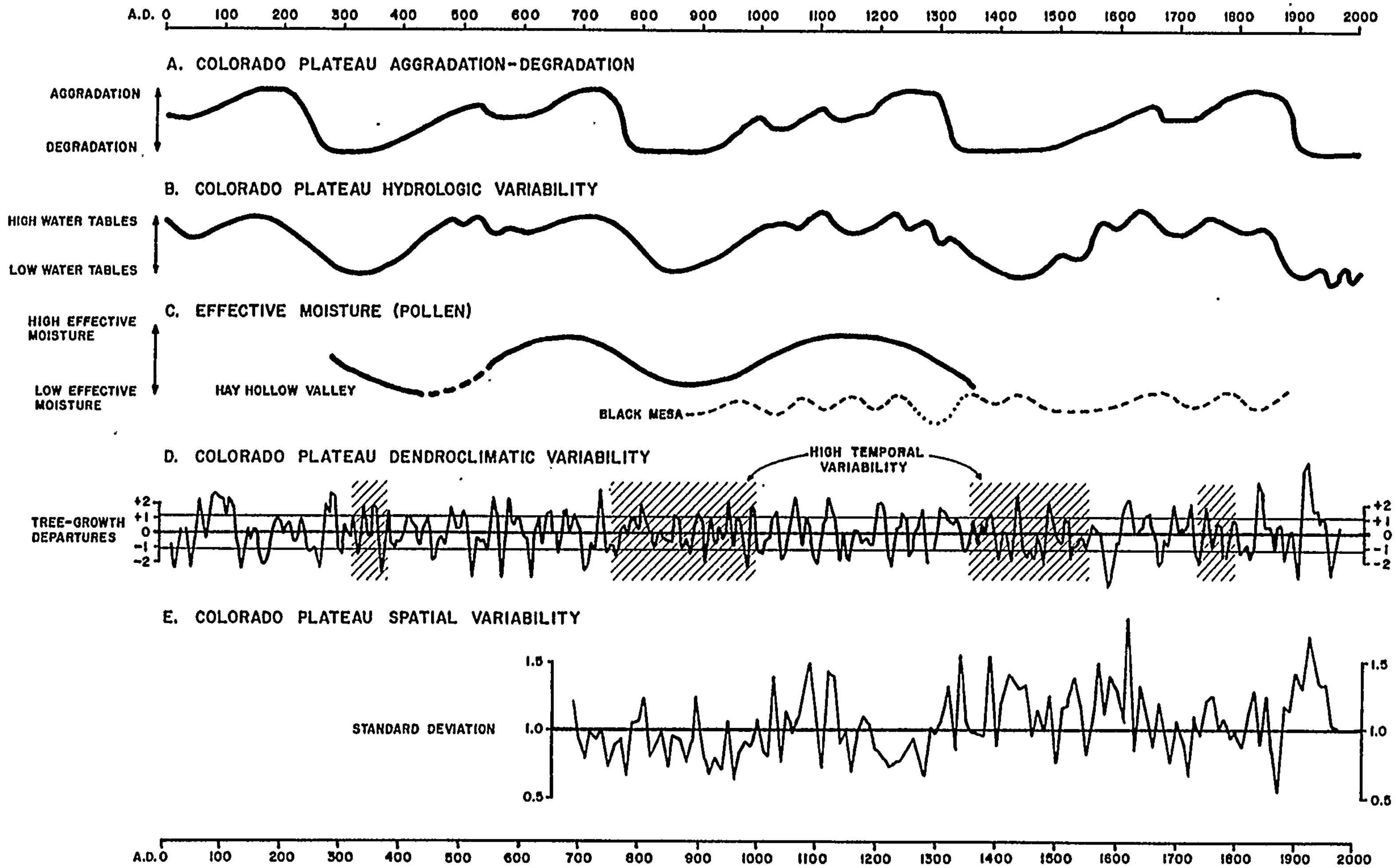


Figure 10. Low and high frequency environmental variability on the Colorado Plateau: A, deposition and erosion of alluvium; B, primary and secondary variations in alluvial groundwater levels; C, fluctuations in effective moisture; D, decadal variability in relative dendroclimate expressed as standard deviations from the long term mean (hatching indicates periods of high temporal variability); E, spatial variability in dendroclimate measured by the standard deviations of chronology station values for each decade.

Comparison of the various environmental records discussed above reveals periods of time in which environmental deterioration is likely to have exerted a major influence on human adaptive behavior on the Colorado Plateau. But even extreme external conditions probably would have had minimal effect until regional populations reached absolute levels and/or local densities that inhibited simple responses such as moving to an unaffected locality or altering local mobility patterns (Plog et al. 1988). Thus, major adaptive behavioral responses to environmental adversity should not be expected until after A.D. 1000 when regional population reached a critical level (Dean et al. 1994).

Major depositional and hydrologic stress would have occurred during periods characterized by floodplain erosion (Figure 10A) and falling or low water tables (Figure 10B). Primary degradation of this sort characterized the A.D. 750 to 925, 1275 to 1450, and 1875 to the present intervals. Secondary fluvial minima were centered on A.D. 1150 and 1700. Effective moisture fluctuations paralleled hydrologic variability and would have exacerbated major crises due to the latter in the A.D. 800 to 1000 and 1250 to 1400 intervals and would have reinforced favorable conditions between 1000 and 1250. Low frequency aspects of climatic variability would have modified the hydrologic and vegetational fluctuations. High temporal variability would have provided enough decade-to-decade variability to moderate adverse fluvial and effective moisture conditions during the A.D. 750 to 1000, 1350 to 1550, and 1730 to 1800 intervals. Greater climatic persistence would have reinforced the favorable hydrologic conditions of the intervening periods. Low spatial variability, on the other hand, would have exacerbated inimical hydrological and effective moisture conditions between A.D. 700 and 1000 and between 1150 and 1300 and tempered the favorable conditions between 1700 and 1900. The climatic instability and changes in seasonal precipitation patterns caused by the disruption of the long-term regional configuration between A.D. 1250 and 1450 would have significantly aggravated the other major low and high frequency environmental degradations of this period. High frequency amplitude variability in dendroclimate would have (1) reinforced unfavorable low frequency conditions in the middle 1100s, late 1200s, middle 1400s, and early 1900s, (2) moderated unfavorable conditions in the early and late 1400s, around 1700, and in the early 1900s, (3) reinforced favorable conditions in late 1000s, early 1100s, early 1200s, early 1600s, and middle 1800s, and (4) moderated favorable conditions in the middle and late 1000s, late 1500s, early 1700s, and early 1800s.

Comparison of various paleoenvironmental records reveals several periods of seriously decreased environmental potential. The severest of these undoubtedly was that between 1250 and 1450 when hydrologic conditions, effective moisture conditions, temporal and spatial climatic behavior, the breakdown in the seasonal patterning of precipitation, and a prolonged drought combined to depress environmental potential across a wide spectrum of variation. Secondary environmental depressions, involving both hydrologic and climatic factors, occurred around A.D. 1150 and 1700. Lesser stress periods occurred in the 1500s and early 1900s. These are intervals in which major, regional scale adaptive culture changes should be expected across the Colorado Plateau. On the other hand, the A.D. 925 to 1130 and 1750 to 1850 periods were characterized by especially favorable low and high frequency conditions.

BEHAVIORAL IMPLICATIONS OF THE PALEOENVIRONMENTAL RECONSTRUCTIONS

Obviously, the potential for comparing past environmental variability with human activities on the Colorado Plateau is virtually limitless and is an exercise that has captivated archaeologists and natural scientists throughout the history of scientific endeavor in the Southwest. While this is not the place to go into this topic in detail, a few observations illustrating the potential of these reconstructions for better understanding the prehistory, and perhaps the future, of the region are warranted.

As has been noted before, the expansion of the most complex manifestation of Anasazi culture, the Chacoan regional interaction system, took place during a period of particularly salubrious environmental conditions (Dean 1993). The Chacoan expression reached its cultural apogee and maximum geographical extent during the favorable A.D. 925 to 1130 period and began to contract during the 1130–1180 interval of environmental stress. It seems quite likely that the advantageous conditions of the 11th century at least facilitated, if not impelled, the Chacoan expansion and that the rather sudden environmental deterioration in the middle 1100s helped trigger the Chacoan decline.

The coincidence of the worst environmental degradation of the last two millennia with one of the greatest cultural upheavals in the span of human occupation of the Plateau virtually demands consideration. The A.D. 1250–1450 interval was a period of great human change throughout the Plateau and the Southwest. Major population dislocations occurred, including local rearrangements, the abandonment of the San Juan drainage, and major population movements into the Little Colorado River drainage, the Mogollon Highlands, and the Rio Grande Valley. Agricultural intensification, involving increased irrigation and more sophisticated dry farming, occurred throughout the region. Important settlement transformations included greater site diversification, extremely large towns, hierarchical settlement systems, and the rise of new occupation centers. Interareal interaction and exchange increased. Socioreligious ideas and organizational principles were elaborated. Widespread cultural stability was not reestablished until the environmental situation ameliorated after A.D. 1450. While it would be foolish to attribute the changes that occurred after 1250 solely to environmental disruption, it would be equally unwise to ignore this potent source of cultural and demographic upset as an important contributing factor in the social transformations that characterized this interval.

Although relating past human behavior to paleoenvironmental variability is a daunting task, hindsight makes it an easier job than trying to extrapolate environment-behavior relationships into the future. Nevertheless, it is possible to suggest some possible future environmental effects on uranium mill tailings disposal and environmental restoration activities on the southern Colorado Plateau.

Given the mandated multicentury longevity for uranium mill tailings repositories, the possibility that even natural processes that have been "stable" during the last two millennia may transgress periodic thresholds and initiate environmental changes must be acknowledged. Earthquakes and/or volcanic eruptions could rupture waste containment facilities or alter the topography of disposal sites. Natural or anthropogenic climatic transformations (due, for example, to changes in ENSO behavior, global warming, or CO_2 enrichment) could alter the ambient weather and biotic environments of the containment sites. Changes in such "stable" factors also would affect efforts to restore damaged environments.

Low frequency climatic and hydrologic fluctuations also could impact waste disposal and habitat restoration efforts. Climatic amplitude changes involving increasing or decreasing precipitation or temperature would alter both the climatic and biotic parameters of waste disposal sites and either inhibit environmental damage mitigation or steer it in unexpected directions. Resumption of high temporal variability will elevate the occurrence frequency of climatic extremes, which would increase disturbance, alter the biota of waste containment facilities, and change the environmental boundaries of both pristine and disturbed habitats. The return of low spatial climatic variability will reduce between-locality environmental differences, which would have little impact on radioactive waste disposal but would tend to limit habitat diversity and the scope of environmental regeneration. The resumption of regional deposition and alluvial water table accretion could directly impact some waste containment sites through burial, groundwater saturation, and even inundation, and it will alter the local environments of some of these facilities and the nature of the biotic threats to their stability. Through their effects on the boundary conditions that regulate valley floor environments, the hydrologic changes will alter floodplain habitats and the nature and possibilities of riparian restoration.

Finally, high frequency climatic fluctuations should have little direct impact on waste disposal and environmental restoration as long as variability remains within the boundaries established by prevailing stable conditions and low frequency processes. When such thresholds are breached, however, high frequency variability could impact waste containment facilities directly or through effects on local flora and fauna. Variations that exceed the "normal" range of high frequency variability could have adverse effects as well. For example, severe storms could damage waste storage facilities either directly or through runoff, while drought could adversely affect the local biota. Positive or negative extremes also would constrain habitat restoration.

CONCLUSIONS

Dendroclimatic retrodictions of past environmental variability are characterized by unusually high sensitivity and chronological resolution. Nevertheless, they are most informative when used in conjunction with other paleoenvironmental indicators because the variables and the reconstruction methods are sensitive to different environmental phenomena and to different wavelengths of variability. Integrated reconstructions illuminate the full range of potential variability and identify periods characterized by unusually detrimental or favorable environmental conditions. These indications can then be used to refine investigations of human adaptive behavior across the region. These reconstructions also provide baseline data for assessing likely environmental impacts on future activities such as the containment of uranium mill tailings and the repair of human environmental damage.

An indisputable outcome of paleoenvironmental research on the Colorado Plateau is the demonstration that modern records do not capture the full range of environmental variability. Therefore, these records cannot be used to estimate potential environmental impacts on future activities in the region. Only detailed, high resolution paleoenvironmental reconstructions provide an adequate empirical basis for long-term environmental planning. The work done so far provides only a glimpse of the possibilities along these lines. Much more environmental, archaeological, ethnographic, and historical research is necessary to enhance knowledge of human and natural phenomena in the region, to elucidate the interactions among human and natural systems, and to provide a sound theoretical and empirical foundation for planning future activities on the Colorado Plateau.

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INTERACTION OF PREHISTORIC CLIMATE, ECOLOGY, AND CULTURES: AN EXAMPLE FROM THE DOLORES RIVER REGION OF SOUTHWEST COLORADO

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Keywords: *pollen analysis, southwest Colorado, climate change, Medieval Warm Period, Little Ice Age, Anasazi*

ABSTRACT

According to the greenhouse theory, during the next few decades global climatic variation will exceed the historical records as the lower atmosphere warms in response to a rise in the concentrations of carbon dioxide, methane, and other gases. The sharp contrast between the large predicted future change and the small climatic changes recorded during the last century indicates that this later period may offer an insufficient basis for appreciating the projected future climate and vegetation changes. Examination of larger-than-historic climatic changes that have occurred in the past (such as those in the Dolores River region) provide a context for evaluating possible future changes and their implications for environmental restoration and land use planning.

The zenith of Anasazi Pueblo Indian occupation in the northern Colorado Plateau region of the southwestern U.S.A. coincides with the Little Climatic Optimum or Medieval Warm Period (AD 900–1300), and its demise coincides with the commencement of the Little Ice Age (AD 1250–1300 to AD 1850–1890). Pollen and tree-ring derived indexes of winter (jet-stream derived) and summer (monsoon derived) precipitation and growing season length were developed for the La Plata Mountains region of southwestern Colorado. The results show that during the height of the Little Climatic Optimum (AD 1000–1100) the region was characterized by a relatively long growing season and by a potential dry farming zone or elevational belt (currently located between 2000 m and 2300 m elevation) that was twice as wide as present and could support Anasazi upland dry farming down to at least 1600 m, an elevation that is quite impossible to dry farm today because of insufficient soil moisture. This expanded dry-farm belt is attributable to a more vigorous circulation regime characterized by both greater winter and summer precipitation than that of today. Between AD 1100 and 1300 the potential dry-farm belt narrowed and finally disappeared with the onset of a period of markedly colder and drier conditions than currently exist. Finally, when the Little Ice Age terminated in the mid AD 1800s and warmer, wetter conditions returned to the region, another group of farmers (modern Anglos) were able to dry farm the area. If conditions like those of the Medieval Warm Period were to return in the near future due to the effects of greenhouse warming, such conditions would be very beneficial to dry farmers in the regions.

INTRODUCTION

Anyone visiting the prehistoric ruins in the American Southwest leaves with a sense of respect for the ancient dwellers, the construction of their dwellings, and the balance they achieved with nature. The latter aspect is particularly interesting because these ancient people relied so heavily on agriculture in an area recognized for its arid climate and, in some regions, relatively high elevation. The earliest populations that are dated before the time of Christ were originally hunters and gatherers, but during the last 2000 yr they have evolved into three culturally distinct traditions upon stimulus from Mexico (Cordell 1984). These include the Mogollon or Western Pueblo, the descendent and more widespread Anasazi Pueblo of the northern Southwest, and the regionally restricted Hohokam culture, which was confined to the Salt and Gila River drainages of southern Arizona. By AD 900 (Figure 1), these cultural traditions had developed advanced and flourishing societies, farming corn, beans, and squash; and supplementing their diet by hunting and gathering or raising food, such as turkeys.

By AD 1100 the Anasazi (which, in this case, also includes the corn-growing Fremont and Sevier-Fremont groups of present-day Utah) had reached their most northern extension. Around AD 1200, long before any Europeans —or even the Navajo or Apache Indians— arrived in the region, the Anasazi began to abandon most of their former northern territory (currently Colorado and Utah). At the same time, the population in the Rio Grand Valley began to expand rapidly, probably from migration, and it continued to grow until its peak at about AD 1300. Other Anasazi groups migrated to parts of Arizona. By AD 1300, the area of Utah and Colorado no longer had evidence of Indian farmers growing corn, suggesting the region had been vacated and during the succeeding several centuries the population of the remaining territory was reduced as other Indian groups and Europeans moved into the southwest United States. However, the Anasazi did not disappear; they probably were assimilated by the Hopi, Zuni, and other modern Pueblo Indians of northern Arizona and New Mexico, some of which still exist today.

Presented here is a specific case study of the Anasazi farmers of the Four Corners region (where Utah, Colorado, Arizona, and New Mexico meet), focusing on the timing, nature, and range of climatic and vegetation change coincident with the Anasazi occupation and abandonment of that high plateau region. The precarious nature of farming in the Four Corners region has led a number of researchers to hypothesize that severe climatic deterioration or fluctuations in the past may have affected the Anasazi's ability to grow corn contributing to population movements (e.g., Schoenwetter and Eddy 1964; Schoenwetter 1966; Schoenwetter 1970; Euler et al. 1979; Dean et al. 1985; Gumerman 1988; Dean 1994).

Even today, modern dry farmers of the Four Corners region may be facing a period of dramatic climatic change. According to the greenhouse theory, during the next few decades global climatic variation will exceed the historical records as the lower atmosphere warms in response to a rise in the concentrations of carbon dioxide, methane, and other gases (Houghton et al. 1990). The sharp contrast between the large predicted future change and the small climatic changes recorded during the last century indicates that this later period may offer an insufficient basis for appreciating the projected future climate and vegetation changes (Schnieder 1986). Examination of larger-than-historic climatic change that have occurred in the past (such as those presented herein for the Dolores River region) may provide a context for evaluating possible future changes that could affect future dry farming, and, for the purposes of this workshop, have implications for environmental restoration and land use planning in the region.

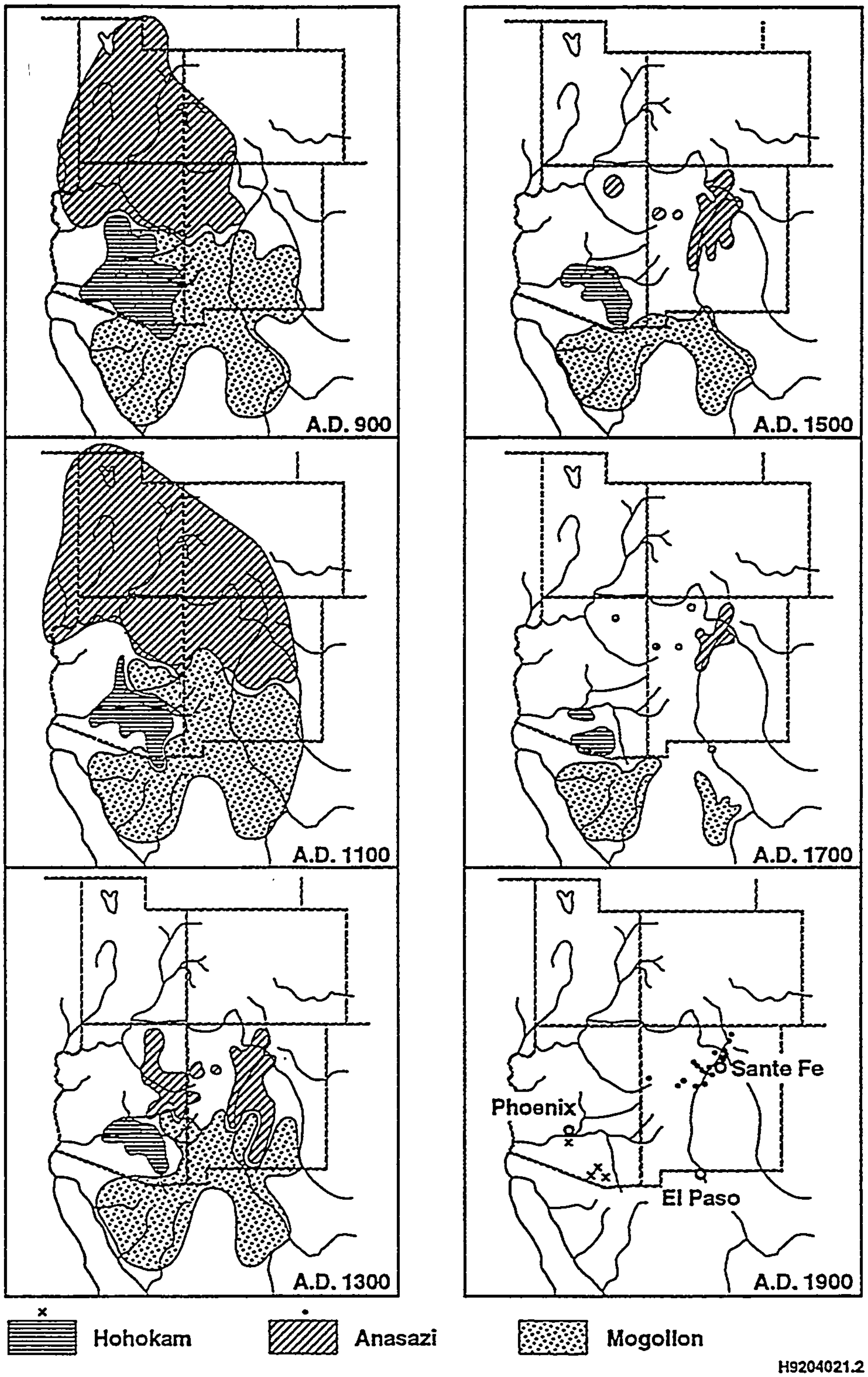

Figure 1. Map showing the approximate extent of Southwest United States Indian cultures at two-hundred-year intervals (redrawn from Jennings 1968).

ENVIRONMENTAL SETTING

The La Plata Mountains of southwestern Colorado are a remote and picturesque mountain group that protrudes into the eastern edge of the Colorado Plateau 30 km southwest of the main San Juan Mountain front. Several peaks in the La Plata exceed 3660 m. The north side of the La Plata Mountains drains into the Dolores River, and the remaining sides flow into the San Juan River (Figure 2).

The precipitation distribution through the year in the Four Corners region is bimodal with pronounced cool and warm season maxima, the latter of which has been recognized as a summer monsoon (Bryson and Lowry 1955; Huntington 1914). The monsoon precipitation in the Four Corners region results primarily from moisture sweeping from the south (Figure 3). South and southeast of the monsoon boundary (and mostly at higher elevations where the growing season is still adequate), the modern dry farmers raise summer crops such as corn, beans, and potatoes. North and west of that monsoon boundary at higher elevation, the soil moisture obtained from winter precipitation is usually adequate to allow dry farmers to raise winter and spring wheat. However, by midsummer soil moisture must be supplemented with irrigation to allow the summer crops to mature.

The climatic differences in the 2300 m of elevational change between the San Juan River and the highest La Plata Mountain peaks provide several vegetation zones. Figure 4 reconstructs the native vegetation circa 1920, which was just before the extensive use of the tractor. The vegetation reconstruction is based on old photographs, historic descriptions, maps, and pollen evidence (Petersen et al. 1985; Petersen et al. 1987).

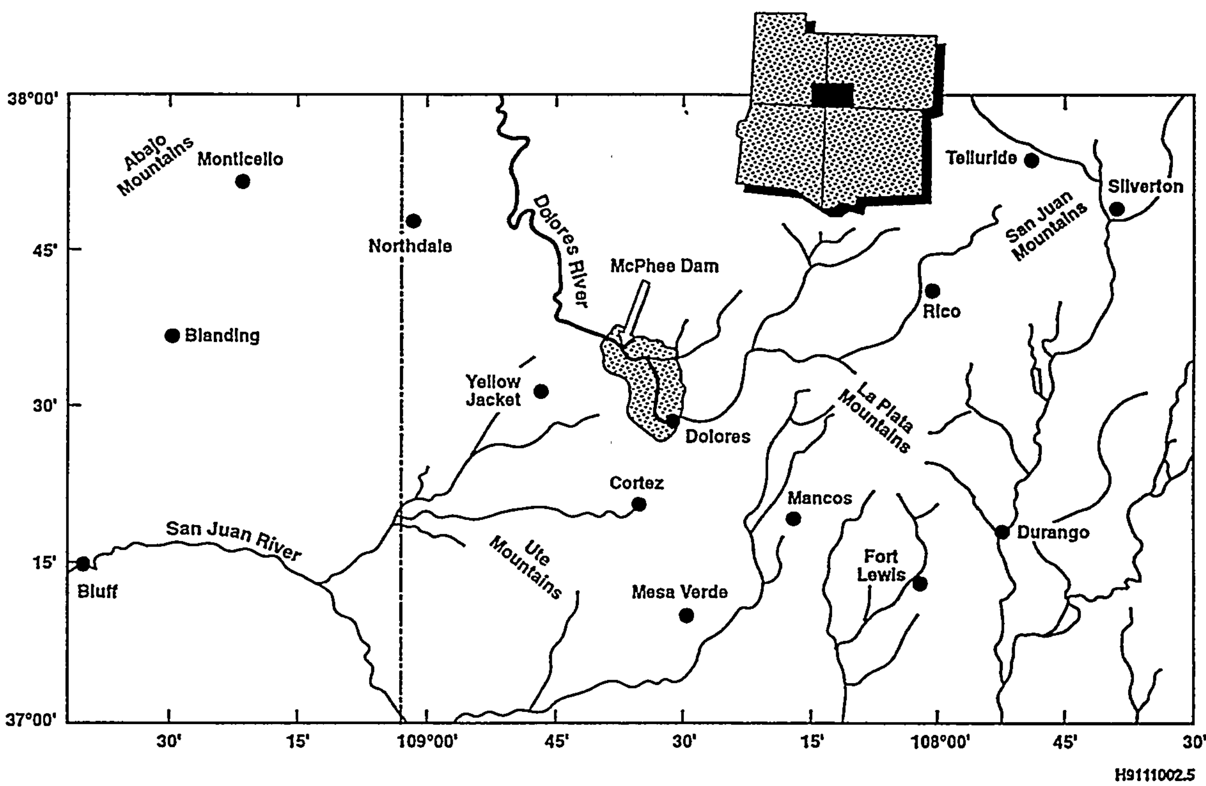

Figure 2. Map showing the location of mountains, the Dolores Project site (shaded), McPhee Dam, and area weather stations in southwestern Colorado and adjacent Utah.

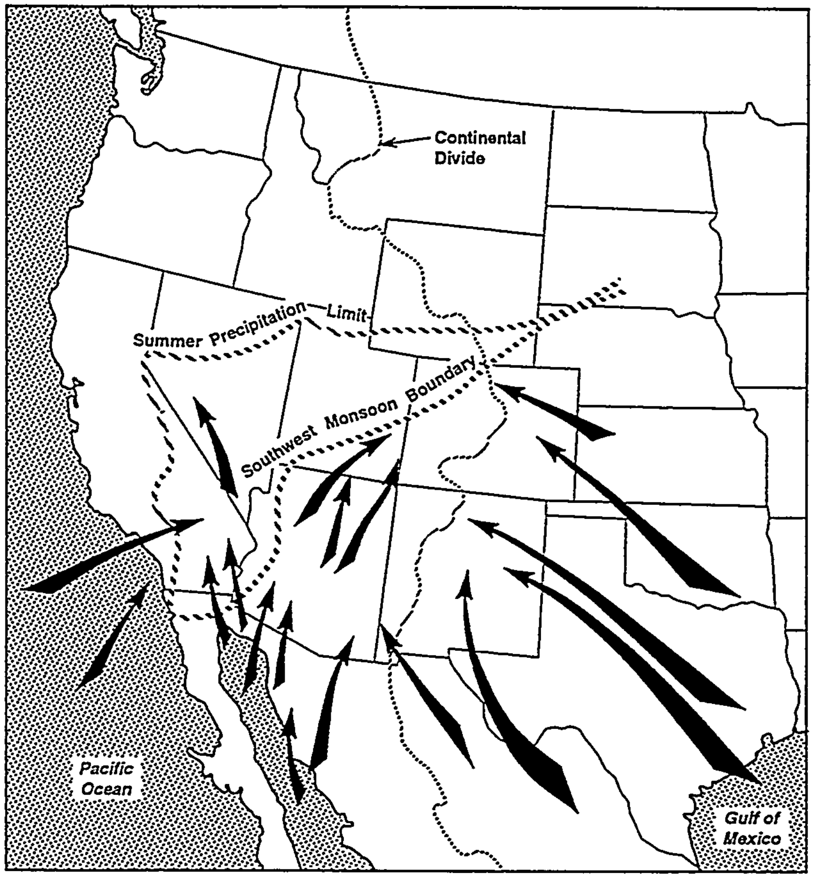

Figure 3. Climatic boundaries for the Southwest monsoon. Precipitation is greatest east and south of the southwest monsoon boundary of Mitchell (1976), where more than half of the annual precipitation occurs during the warm season (Dorrah 1946). North of that boundary the amount of warm season precipitation decreases until it reaches the summer precipitation limit of Pyke (1972). Arrows show the main paths of moisture in the southwest United States during the summer (adapted from Miller et al. 1973).

The extensive stands of sagebrush (*Artemisia tridentata*) that occur to the west of the La Plata Mountains led Newberry (1876:84) to name the divide between the San Juan and Dolores rivers (extending from Mesa Verde west to Comb Ridge, near Blanding, Utah) the "Sage Plain." This sagebrush-covered plateau (10,360 km^2) ranges between 1500 and 2100 m elevation (Gregory and Thorpe 1938). Much of the area today between 2010 m and 2380 m elevation has been cleared of natural vegetation and is under dry-land cultivation. In Figure 4 that zone (or elevational belt) of cultivation represents primarily the higher elevations of the pinyon and juniper, most of the big sagebrush, and the lower elevational limit of the montane scrub mapping units. This relatively narrow agricultural belt is farmable because of the good soils and because it is both wet enough (greater than 35 cm of annual precipitation—of which 10 cm fall during the warm season) and warm enough (including a greater-than-110-day frost-free season) to allow routine dry farming of such crops as corn, beans, potatoes, and grains (Petersen et al. 1987; U.S. Department of Agriculture, Soil Conservation Service 1976).

When farming within this belt, contemporary farmers often discover the cultural remains of ancient Anasazi, who farmed corn, beans, and squash on the same land hundreds of years

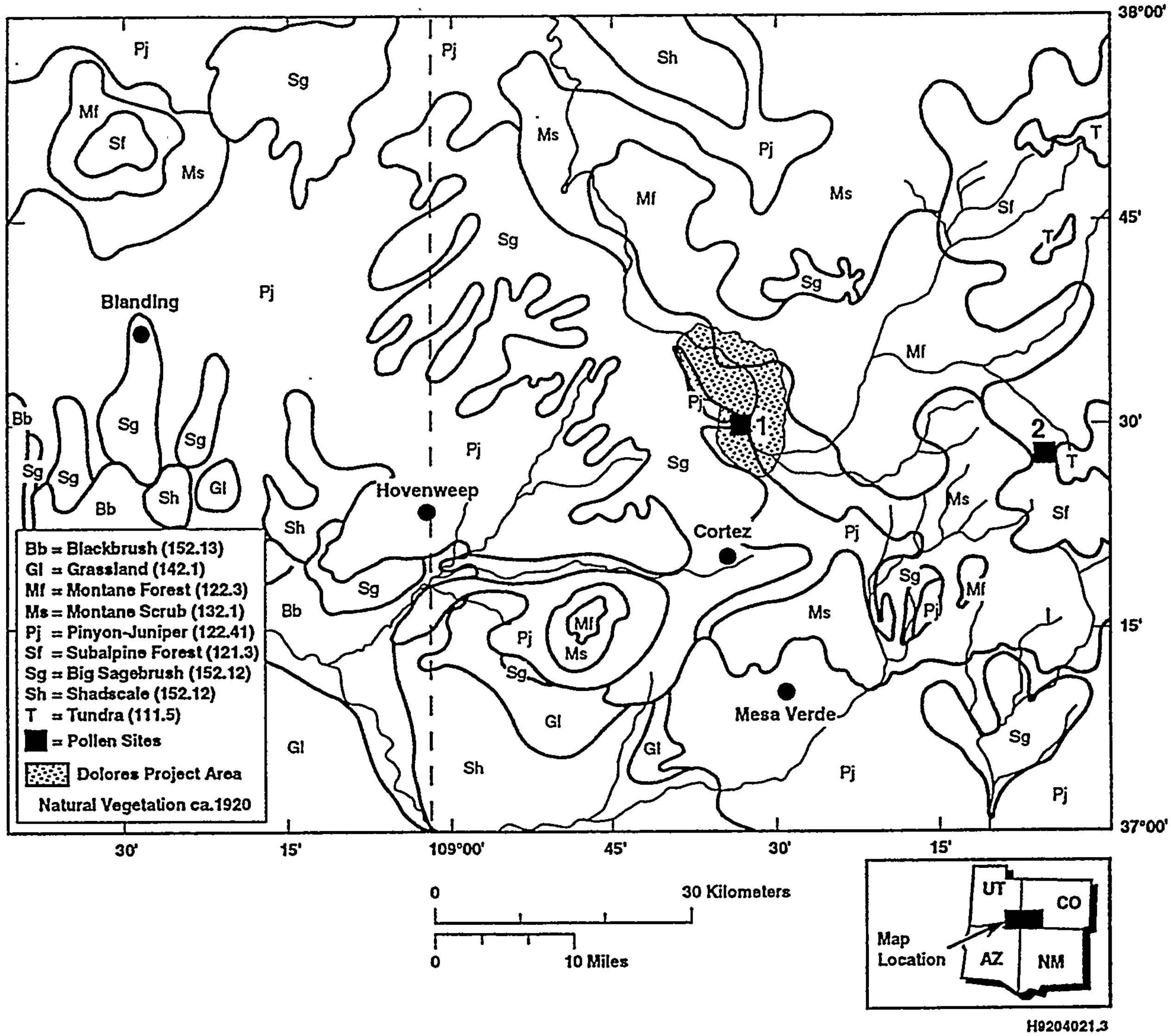

Figure 4. Major plant communities in southwestern Colorado and southeastern Utah, ca. 1920 (Petersen et al. 1987). Numbers in parentheses refer to Brown's (1982) vegetation classification scheme. Black square number 1 shows the location of Sagehen Marsh. Black Square number 2 shows the location of the Beef Pasture and Twin Lakes pollen-coring sites; they differ by 230 m in elevation and are located 5 km apart.

earlier. The flanks of the La Plata Mountains in southwestern Colorado are surrounded by vast areas containing evidence of Anasazi occupation, the most famous being preserved in the boundaries of the Mesa Verde National Park (Osborne 1965; Cordell 1984). Because modern changes in either moisture or summer warmth could affect the width or elevational range of the present potential dry-farming belt, this must also have been true for the Anasazi.

POLLEN, TREE-RINGS AND THEIR HISTORIC CLIMATE CALIBRATION

In this study the prehistoric elevation and width of the dry farming belt is reconstructed and contrasted with that of the present, based on the premise that knowledge of the history of that belt would be useful in unveiling the history of Anasazi settlement and movement. This is because the climatic factors that affect horticulture (i.e., sufficient growing season and moisture for dry farming) are generally the same factors affecting the natural plant community distribution and composition.

The index used for hypothesizing the width of the dry-farming belt is the changing width and elevation of the spruce (*Picea engelmannii*) forest zone in the La Plata Mountains (Figure 5). This index was obtained by analyzing pollen records from two different elevations within the spruce zone (Petersen and Mehringer 1976; Petersen 1988a; Petersen 1994). The lower-elevation record (Beef Pasture) provided a history of the moisture-dependent lower-elevation spruce boundary while the upper-elevation record (Twin Lakes) provided a history of the temperature-dependent timberline. Because spruce growth responds differently to climate variations at different elevations, the combined radiocarbon-dated pollen records from the two sites yield climate information not obtainable from either site alone. In addition, the changing record of pinyon pine (*Pinus edulis*) pollen, which wafted up from the surrounding lowlands and was deposited at the lower pollen site, is used as a measure of the changing number of

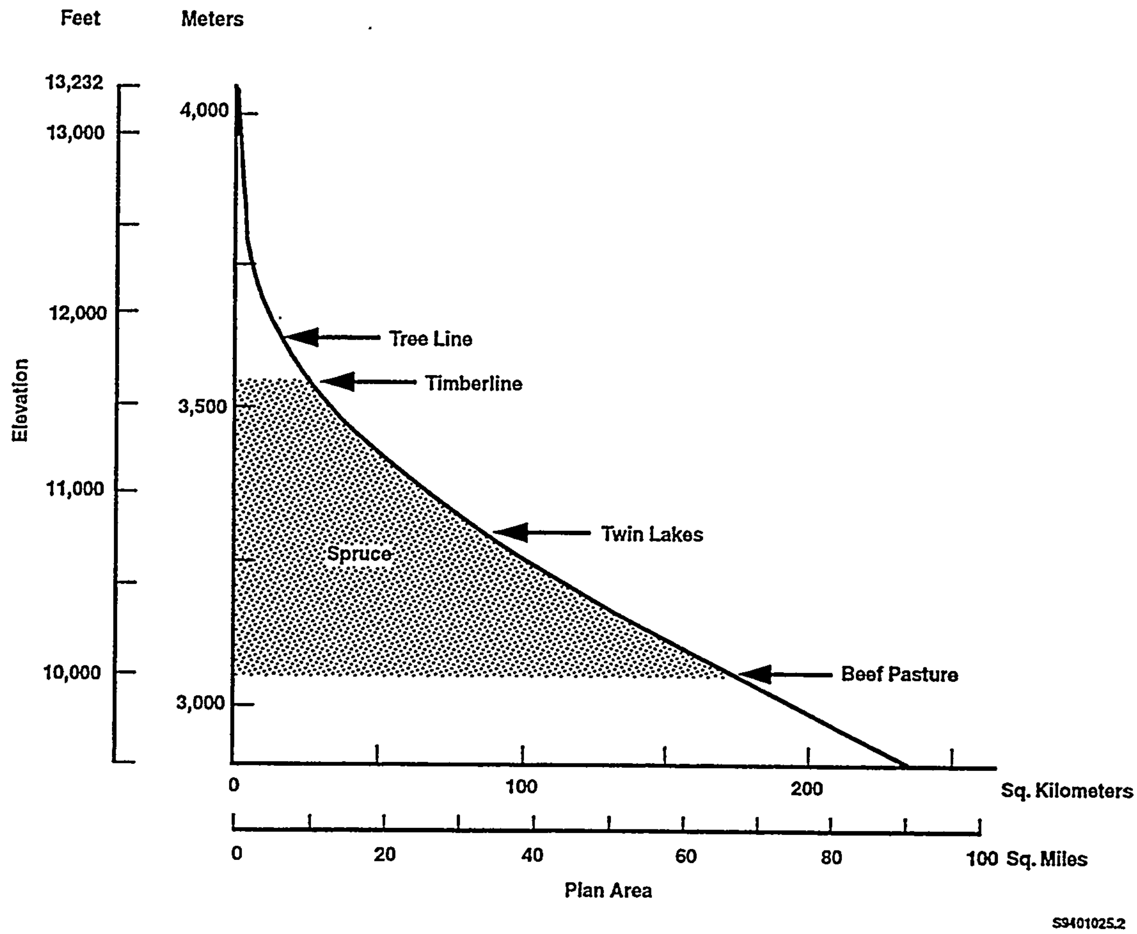

Figure 5. Area elevation graph for 250 km² around Twin Lakes, La Plata Mountains, Colorado. The curve is drawn from a plot of the plan area above each 152-m contour (La Plata, Colorado, 7.5 minute quadrangle), beginning at 2895 m.

pinyon trees on the landscape. A third pollen site (Sagehen Marsh) that occurs within the potential dry-farm belt (Figure 4) was used to verify some of the reconstructions obtained from the pollen records in the spruce forest.

The stippled area in Figure 5 indicates the zone of relatively dense spruce around Twin Lakes in the La Plata Mountains. Results of surface pollen studies and documented historic changes indicate that the large, heavy spruce pollen does not travel very far from the source tree (King 1967; Maher 1963; Wright 1952) and so is a good indicator of the proximity of the trees.

A depression of upper timberline of only 100 m would decrease the area occupied by forest nearly 25 km^2, doubling the area above timberline, and the Twin Lakes location is sensitive to such changes. Beef Pasture's location (at the current lower elevational limit of dense spruce forest) makes it particularly sensitive to the elevational changes in that boundary.

Age determination of vegetation change in the La Plata Mountains is aided by 17 radiocarbon dates and a computer clustering program used to segregate adjacent pollen samples from each of the two sites into similar groups which were then correlated to one another (Petersen 1988a; Petersen 1994). The pollen sample ages were converted from the estimated radiocarbon ages derived from tree-ring calibrated calendar dates (Damon et al. 1974; Klein et al. 1982; Stuiver and Reimer 1986; see Petersen 1994 for a more detailed discussion).

Figure 6 shows radiocarbon dates, estimated calendar dates, pollen zones, and pollen ratios for a portion of the combined Twin Lakes and Beef Pasture pollen records. Calibration of changes in the prehistoric record in Figure 6 is aided by paying special attention to the changes evident in the last 150 years or so.

At Beef Pasture the spruce to pine pollen-ratio curve was selected as the best record of the movement of the lower limit of the spruce forest. The only pines that grow in the La Plata Mountains are pinyon and ponderosa pine and they both grow at elevations below Beef Pasture. To visually display the relative elevational changes in the lower forest border (Figure 6) the ratio value is plotted on a negative y-axis that starts at zero and increases downward. Thus, increases in the spruce/pine ratio at Beef Pasture are plotted farther from the origin and represent, relatively, a lowered elevational limit for the lower spruce zone boundary.

Repeat photographs in the La Plata Mountains and surrounding regions document historic expansion to lower elevations and the thickening of the lower spruce forest border over the last 100 yr (Petersen 1988a). This expansion seems to corresponds to a concomitant increase in effective moisture early this century, primarily in the form of increased winter or spring snow pack the highest in the last 400 yr (Stockton 1976; Thomas 1959). Spruce is relatively shallow rooted and cannot tolerate much soil drought, so a decrease in effective moisture would be detrimental to tree survival, while an increase would foster a downward expansion (Daubenmire 1943; Dix and Richards 1976; Pearson 1931).

At Twin Lakes, the proportion of conifer pollen (spruce + fir + pine) to pollen from nonarboreal plants (NAP) is selected to represent the relative fluctuations of the timberline (Figure 6) as it has been done in Europe (e.g., Patzelt 1974). This ratio, rather than that used at Beef Pasture, was chosen because the Twin Lakes area recently was logged, thus artificially removing some spruce trees and affecting the modern Twin Lakes spruce-to-pine ratio. The ratio of all conifers to NAP was used to offset the effect of modern logging because less weight is given specifically to spruce in the ratio.

Repeat photographs document that the tree-line in the La Plata Mountains has risen about 50 to 100 m in the last 100 yr, and there has been a concomitant change in tree-growth form at the tree-line where krummholz form has

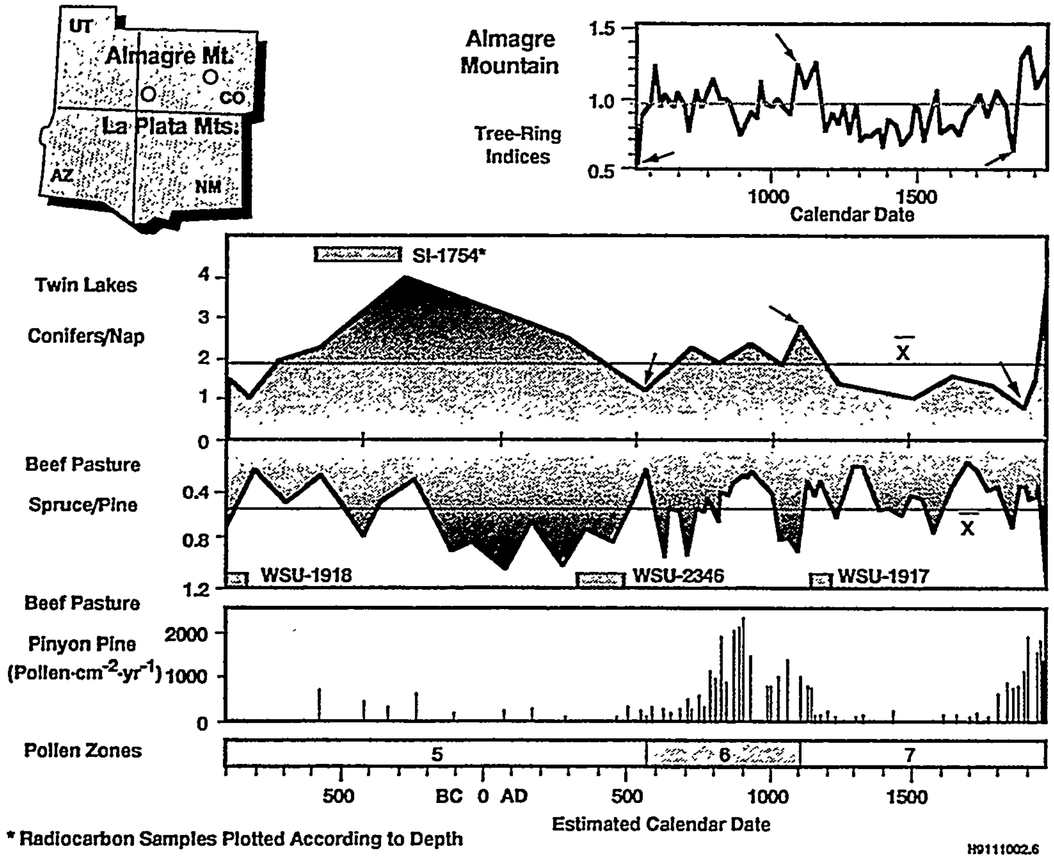

Figure 6. Pollen ratios from Twin Lakes and Beef Pasture pollen sites in the La Plata Mountains drawn so that they emphasize the relative width of the spruce forest through time as compared to a record of high-elevation bristlecone pine tree-ring indices from central Colorado (LaMarche and Stockton 1974), and an estimate of the number of pinyon pollen grains deposited during 1 year at Beef Pasture on a 1 cm^2 surface. Arrows indicate points believed to correlate.

changed to non-krummholz growth form. Rings from trees at timberline have changed from narrow to wide, coinciding with the extension of the growing season at the lower elevation during part of the same time period (Petersen 1988a). Because the major limiting climatic factor for tree growth near timberline is summer temperature (Daubenmire 1954; Tranquillini 1979; Wardle 1974), these changes most likely indicate an increase in summer temperature from last century to this century.

The present high pollen ratios at the modern surface of Twin Lakes and Beef Pasture (Figure 6) may be too high. Thousands of hectares of sagebrush and pinyon pine were cleared by modern farmers in the region after 1920 (Petersen et al. 1987). Because these plants are wind pollinated, their pollen is widely distributed beyond the source plants. Extensive removal (such as the clearance by farmers) of these pollen sources would tend to decrease their proportion in the pollen rain deposited. Possibly the unbiased ratio lies lower than the modern, but higher than the mean lines shown in Figure 6. At Beef Pasture, the ratio values of $\geq$ 0.60 are considered representative of conditions similar to those that have occurred historically, and values lower than these are considered reflective of drier conditions than present.

In this study, long tree-ring records from high-elevation trees near timberline were sought as a climate proxy to be compared with the La Plata Mountain pollen record. A model of the relationship between tree growth and climate has been devised by Fritts (1976) that shows that stored food reserves are the link between the previous year's climate and current year's growth. In high elevation trees food reserves are primarily constrained by summer temperature. The summer must be long enough or warm enough to allow production of adequate food reserves to be used for respiration, needle replacement, and next year's ring production; larger surplus values correlate to wider rings.

LaMarche and Stockton (1974) obtained ring width records for high-elevation bristlecone pine (*Pinus aristata*) from Almagre Mountain (near Pikes Peak, Colorado). The Almagre record was selected for this study because it was the longest regional tree-ring record from upper timberline. The yearly indices (Drew 1974) were used to obtain averages of successive 20-yr means and plotted on the 11th year (Figure 6). Points believed to correlate between the Almagre and Twin Lakes records are indicated by arrows.

The bottom panel of Figure 6 plots the number of pinyon pine pollen grains falling on a 1 cm^2 surface area during 1 yr at Beef Pasture. Changes in pinyon pine pollen absolute influx values are especially evident for the past 150 yr with a pronounced increase followed by a very recent decrease after the turn of the century. These changes actually reflect the recent history of pinyon trees to the west of the La Plata Mountains. Beginning last century, pinyon has been expanding its range in the Four Corners region (Erdman 1970:21; Spencer 1964:148; Van Pelt 1978). That trend probably would have continued everywhere in the Great Sage Plain, except for the extensive clearing for farming especially evident after 1920 due to the widespread use of the tractor. The record at Sagehen Marsh has even tighter chronological control and clearly records the same pattern (Petersen 1985; Petersen et al. 1987).

Summer rainfall seems especially critical for pinyon seedling establishment and for subsequent tree growth. Physiological adaptations such as shallow roots in addition to deeper roots, a large seed that aids rapid and deep radical penetration, needle form and number, cuticle thickness, and small growth form all seem to be special adaptations that take advantage of summer monsoon precipitation after the droughty month of June (Daubenmire 1943:11; Emerson 1932; Wells 1979:318). In addition, there is a coincidence between the geographical distribution of summer monsoon rainfall in the western United States and the distribution of pinyon pine. When the monsoon is weak, it arrives later, does not penetrate as far to the northwest (Figure 3), and leaves earlier and pinyon seedling establishment is hindered. When it is strong, just the opposite is true (see Petersen 1985, 1988a for additional discussion).

In short, the direction of pollen changes shown in Figure 6 for the last 150 years match the direction of vegetational change that has been documented for the region—the spruce forest in the La Plata Mountains has expanded at both its upper and lower margins and pinyon has expanded its range into sagebrush dominated lands. These changes could be explained by a combination of the higher winter snowpack and a strengthening of the summer monsoon. It is as if there were greater vigor in the general circulation regime whereby more oceanic climate (both summer and winter) was being pulled deeper inland to affect the Four Corners Region. And as touched on, San Juan River runoff for the period 1907 to 1932 had the greatest sustained runoff period of the last 360 years as reconstructed from tree rings (Stockton 1976:430–31). See Wallen (1955) and Petersen (1988a) for a more detailed discussion of a possible explanation for the particular circulation patterns which seem especially favorable for expansion of pinyon and the width of the spruce zone.

CLIMATIC RECONSTRUCTION

The reconstructions of the dry farming belt width presented in Figures 7 and 8 are based on an interpretation of the climate indices in Figure 6. The combination of Colorado Front Range tree-ring width data with the Twin Lakes conifers/NAP pollen ratio is used to locate the upper elevational limit of the dry-farm belt and described in terms of growing season length. The Beef Pasture spruce/pine ratios are used to locate the lower elevational extent of the dry-farming belt (supplemented with archaeological site distribution data as discussed below) and described in terms of jet-stream derived winter precipitation. Finally, pinyon pine pollen influx is used to evaluate the risk for dry farming within the farm belt and also is used to characterize the strength of the summer monsoon. The pattern shown in Figure 7a is the historic pattern and represents the reconstruction for the period AD 600–800.

At the beginning of the AD 600–800 period, after the very narrow spruce zone centered about AD 550, the Almagre tree-rings show a very rapid increase in width. At that time the Anasazi began appearing in large numbers in southwest Colorado (Schlanger 1988), which coincides with the region emerging from the grips of cold weather of the 6th century. The rapid warming widened the dry-farming belt to about the same size it is today. The pollen samples dating to the mid AD 600s from Sagehen Marsh in the Dolores Project area are indistinguishable from the pollen samples that date shortly before the 1920 clearing (Petersen 1984, 1988b; Petersen et al. 1987). During this period populations grew and the Anasazi thrived.

Beginning about AD 750, long-term winter drought moved into the area and the agricultural zone narrowed by about half of that today (Figure 7b). That winter drought continued for about 200 yr; however, it was offset somewhat by increased summer convective storms that more commonly discharged precious moisture near the elevation of the potential dry-farm belt, rather than at lower elevations (Farmer and Fletcher 1971; Petersen et al. 1987). The large population increases that occurred in the Dolores Project area at that time cannot be accounted for by births alone, suggesting that the Anasazi survived by moving their fields to higher elevations and exploiting the narrowed (but still productive) farm-belt (Schlanger 1988). Historic documents show that about half the farm land in the region was abandoned during the severe drought of the 1930s, providing an analog for a narrowed dry-farm belt (Gregory and Thorpe 1938; Petersen et al. 1987).

There is a period of narrow tree-ring widths in the Almagre record that dates to the 10th century (Figure 6). A further test of the correlation between narrow tree-rings and summer warmth or growing season length is provided by Dolores Project archaeological data. Areas subject to cold air pooling, such as the Dolores Canyon proper, were mapped in the Dolores Project area, and it was found that although the canyon had been almost continuously occupied since the 7th century, it was suddenly abandoned by Anasazi farmers for a short time in the 10th century when the Almagre tree-ring record suggests cooling. The farm land was again reoccupied in the 11th century when tree-ring width at timberline again became wider (Breternitz et al. 1986; Petersen et al. 1987).

By AD 1000, the climate had warmed to a point that growing season was adequate for farming in the Dolores Project area, and the summer monsoons' moisture was supplemented by a large increase in the amount of winter precipitation. This combination greatly expanded the farming belt, dropping its lower limit to about 1600 m elevation (Figure 8a), which more than doubled the amount of farmland available, compared to that of today (as shown in Figure 7a).

It is generally accepted that Anasazi dwellings would not be located too far from their corn fields. At Hovenweep National Monument (1600 m), where there are abundant Anasazi ruins, one cannot grow corn today because the

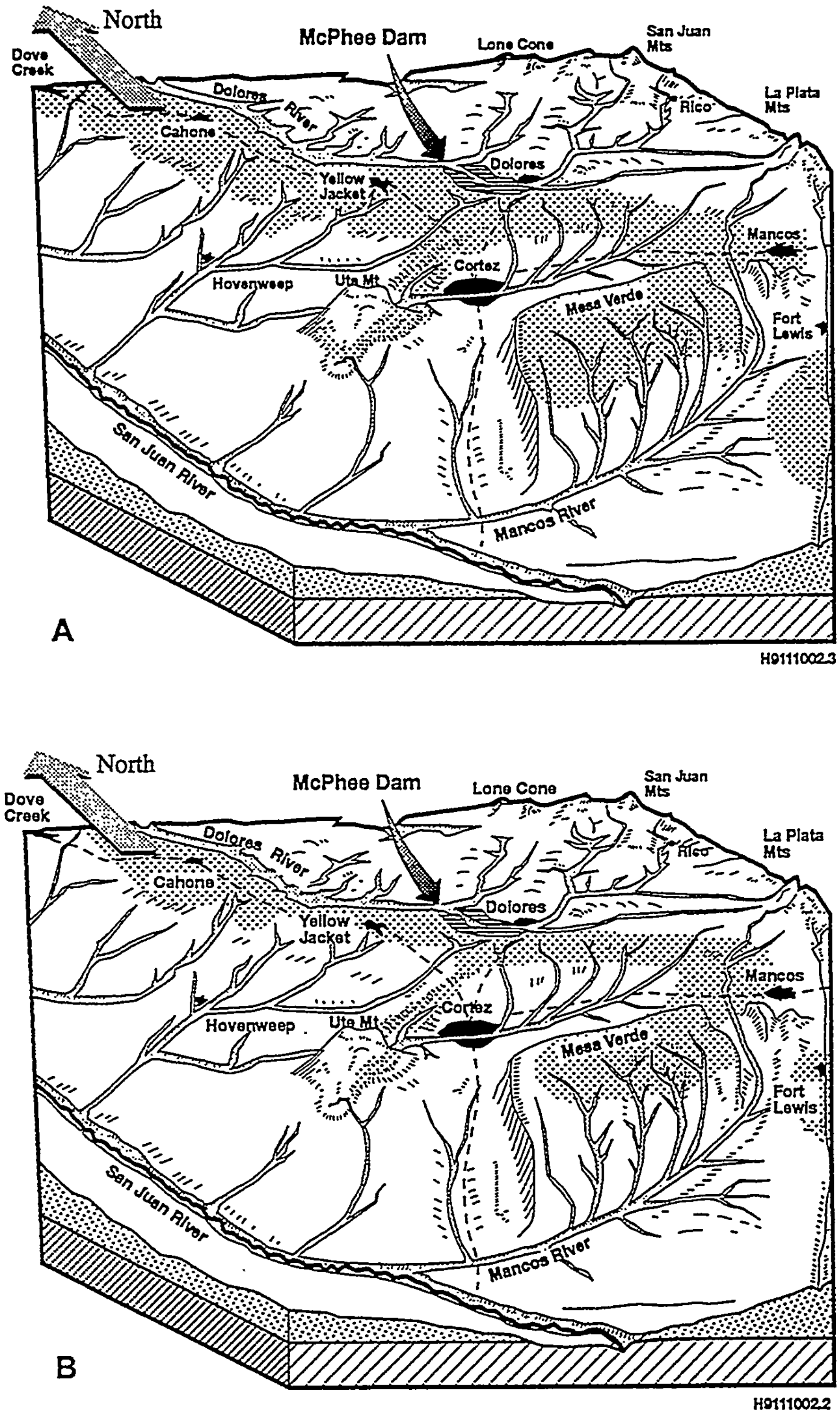

Figure 7. A bird's eye view of the reconstruction of the relative width of the potential dry-farm belt in southwestern Colorado. (A) Modern and AD 600 to 800, (B) AD 800 to 1000 and 1100 to 1300.

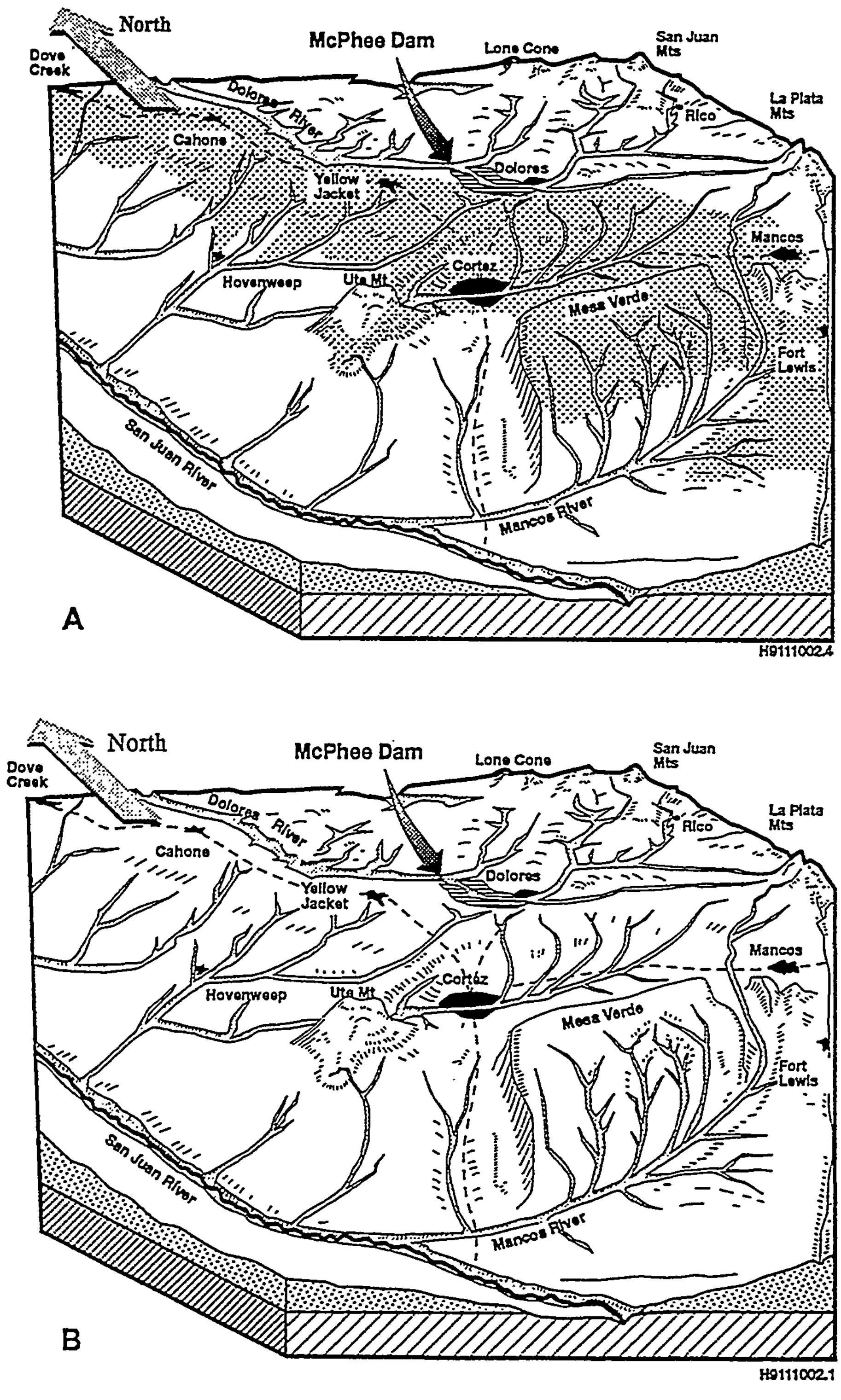

Figure 8. A bird's eye view of the reconstruction of the relative width of the potential dry-farm belt in southwestern Colorado. (A) AD 1000 to 1100, (B) AD 1300 to 1850.

30 cm of annual precipitation at that elevation is not adequate. In fact, modern farmers cannot obtain crop insurance for dry farming for elevations below 1830 m (some 230 m higher in elevation) and routine dry farming is not practiced below 2010 m (Petersen et al. 1987). However, Woosley (1977) found in surface pollen transect on suspected Anasazi mesa-top, dry-farming fields at Hovenweep that there was corn and bean pollen still preserved in the soil by the arid climate. Corn pollen is a relatively large pollen grain that usually does not travel more than a few meters from the source plant and even in modern corn fields is only 1 or 2 percent of the pollen count (Martin 1963:50). To find corn pollen in such upland field locations suggests that conditions for rainfall farming had to have been drastically different from the current conditions.

The period from AD 1000 to AD 1100 actually coincided with the zenith of the Anasazi cultures. During this time period, there was a tremendous explosion in archeological evidence (locally called the Pueblo II expansion) for areas currently below the modern extent of the farm belt. Populations also increased dramatically elsewhere (Figure 1) as did the development of complex social, economic, and political structures, the most famous of which is preserved in Chaco Cultural National Historical Park in northwestern New Mexico. During this time, the monsoon boundary (Figure 3) most likely was located north of its present location.

Soon after AD 1100, another winter drought began to move into the region, narrowing the potential dry-farm belt from the bottom (Figure 7b). As before, the Anasazi began to adjust, but unlike the drought of the AD 800s (Figure 6), summer rain was not as plentiful or dependable, the summer monsoon boundary was most likely located south of its present locations. Summer rains arrived later, left earlier, and were not as predictable. This time the Anasazi compensated by utilizing a number of water control strategies such as check dams, ditches, and reservoirs (e.g., Erdman et al. 1969).

Then severe, dry cold started to move into the region about AD 1200, making farming risky at higher elevations (Figure 6). As the summer and winter drought pinched the farming belt from the bottom, cold pinched it from the top. By AD 1200 the Anasazi began leaving the area. The most severe impact of the combination was felt late in the AD 1200s, where in effect, the farming belt was squeezed to the point that it disappeared (Figure 8b). The Anasazi simply left the higher elevations of the Four Corners region and headed south, seeking more dependable summer monsoons, sufficient winter precipitation (or areas that could be irrigated), and longer growing seasons (Figure 1).

Interestingly, on the basis of Figure 6, the cold, dry conditions that began in the AD 1200s lasted for hundreds of years—without much change—to about the AD 1850s. Because weather stations in the region were mostly established after 1895, somewhat after the change to warmer and wetter conditions that have existed during the last 130 years or so, our modern weather records give little hint of the severity of prior conditions that may have occurred. The climatic conditions during that period is suggested by an account of a military expedition, led by Col. J.N. Macomb, that came into the region in 1859. Newberry (1876:76–77, 88–89) observed a broad surface of snow covering the San Miguel Mountains of the San Juan's in early August (today it is gone by early July). And from atop an extensive Anasazi archaeological site near modern day Yellow Jacket that contained abundant corn grinding implements, Newberry observed that it was *too high*, *too cold* and *too dry* to grow corn and other crops which the prior inhabitants obviously must have grown. Newberry concludes that a dramatic change in climate had to have occurred since the Anasazi occupation.

In the 1870s, some 20 to 30 yr after Macomb's and Newberry's expedition, when white settlers began moving into the area (Figure 7a), the mountain peaks were clear of snow in late summer, young pinyon trees were invading the sagebrush, and the spruce forest was beginning to expand. All these were signs that the farming belt had rebounded and that the new settlers would find ideal dry-farming conditions with abundant summer and winter precipitation and an adequate growing season. The climate had reverted to conditions similar to those during the 700-yr Anasazi occupation, and the modern farms could locate exactly where the Anasazi had farms during their sojourn in the region. Today, the Yellow Jacket locality visited by Newberry supports thousands of hectares of dry-farmed beans and corn (Petersen et al. 1987; Petersen 1988a).

DISCUSSION AND CONCLUSIONS

In the next century, increases in atmospheric trace gas concentration could warm the global average temperature beyond what it has ranged during the past century (Houghton et al. 1990). Some have also suggested that the Medieval Warm Period was on the order of 1°C warmer than today (Lamb 1977; but also see Hughes and Diaz 1994 for exceptions) and thus might serve as a possible analog for potential future warming associated with the increase of greenhouse gases. Finding Anasazi dryland fields as low as 1600 m at Hovenweep during the time period of the Medieval Warm Period suggests that conditions for rainfall farming had to have been drastically different from current conditions. There seems to have been greater vigor in the general circulation manifested locally with greater winter and especially summer precipitation so that soil drought was not the limiting factor at 1600 m that it is today for dry farming corn. If conditions like those of the Medieval Warm Period were to return in the near future due to the effects of greenhouse warming, such conditions would be very beneficial to dry farmers in the region (just as they were to the Anasazi farmers).

Some scientists have suggested, mostly on the basis of tree-ring evidence, that drought forced the Anasazi from the Four Corners region in the 13th century although there had been earlier droughts that were as serious, yet the Anasazi did not leave during those times (Fritts et al. 1965). Possibly, as suggested herein, the drought that affected the Anasazi late in their occupational history *was* different because it was a *cold* drought. As discussed, there was a cold drought earlier in the 10th century shown in Figure 6 that specifically affected Anasazi trying to farm the river bottom of the Dolores River Canyon. Interestingly, the timing of this 10th century cold drought matches the 10th century period of glacial expansion that occurred in Europe and some other parts of the world (Grove and Switsur 1994).

Beginning some thirty years ago, Southwestern researchers (e.g., Berlin et al. 1977; Bray 1971; Bryson and Julian 1963; Martin and Byers 1965; Smiley 1961; Woodbury 1961) suggested that the demise of the Anasazi culture might have some how coincided with the onset of the Little Ice Age. In many parts of the world, the Little Ice Age has been described as a time of lower temperature (on the order of 1°C), renewed glacial activity, expanding snowfields and, in some regions, reduced summer monsoons (Lamb 1977; Grove 1988). However, as additional dates were obtained for Little Ice Age glacial advances they seem to predominately fall within the last five centuries, too late to have a causal link with Anasazi abandonment.

However, the time range for the Little Ice Age does seem to vary depending upon the author. More and more recent evidence is now being garnered to show that the last several centuries contained two glacial advancing phases of approximately equal magnitude. The earlier glacial advance actually did begin during the AD 1250–1300 period (Grove and Switsur 1994) thus coinciding with Anasazi abandonment of the Four Corners Region. Grove and Switsur (1994) further note that the conditions between these two glacial advances did not revert to those obtained before AD 1300, so it seems then to be more appropriate to adopt a broader definition of the Little Ice Age that covers both advance phases and broadens the time range to between AD 1250–300 and AD 1850–1890—a time period that matches the cold, dry period that is shown in Figure 6.

The impact of the Little Ice Age in the Four Corners region appears to have been primarily in the form of winter drought, shorter growing seasons, and a failure of the summer monsoon to penetrate as far north as present. This combination serves to increase the risk of dry farming failure at all elevations and in the 13th century effectively pinched out the potential farm belt.

If conditions similar to either the Medieval Warm Period or the Little Ice Age were again to return to the Four Corners region it would affect modern dry farmers. And in the context of this workshop, such greater-than-historic changes could have specific implications for the future that should be taken into account in environmental restoration and land use planning.

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THE INSTRUMENTAL CLIMATE HISTORY OF SOUTHWESTERN COLORADO

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Keywords: *climate, climatic change, climate data, southwestern Colorado, Four Corners, precipitation, temperature*

ABSTRACT

Instrumental observations of the climate of southwestern Colorado date back to about 1880. Climatic conditions since the late 19th century will be described with emphasis on temperatures, temperature ranges and observed precipitation. Typical seasonal patterns of temperature and precipitation will be shown, and variations and apparent trends over time will be discussed. Drought characteristics will be described based on a standardized precipitation index developed for Colorado. Finally, brief comments on the challenge of collecting accurate and consistent long-term data will be given.

INTRODUCTION

The instrumental climate history refers to the period during which objective measurements of climatic elements, such as temperature and precipitation, have been taken using standard meteorological instruments. Nationally, this represents little more than 150 years (Fleming 1990)—a mere blink of the eye in comparison to the time scales over which archaeologists, paleoclimatologists and geologists have identified and described past climate changes. For the many remote areas of the western U.S., such as the Four Corners region, instrumental climate histories are even shorter. Although brief, the instrumental climate record is essential for providing a reference platform from which to describe the present climate. It then becomes possible to compare climates of the past and to imagine climatic conditions of the future. The instrumental climate record also offers the opportunity to evaluate interannual and interdecadal variations that are a challenging but normal part of our climate system.

DATA AVAILABILITY

The Colorado Climate Center routinely monitors climatic conditions throughout Colorado and evaluates current conditions with respect to what has been observed throughout the instrumental record. This paper focuses on several aspects of the climate of southwestern Colorado within the region identified in Figure 1.

The earliest instrumental climate records in Colorado were begun in 1852 at Fort Massachusetts in south central Colorado (Doesken et al. 1991). The U.S. Army Post at Fort Lewis was the earliest weather station in southwestern Colorado with observations beginning in 1880 (Bradley and Barry 1973). Beginning after 1890, the number of weather stations increased as the newly formed civilian U.S. Weather Bureau made nationwide climate monitoring a priority to support the growth of U.S. agriculture. Volunteer weather observers were recruited, supplied with standard

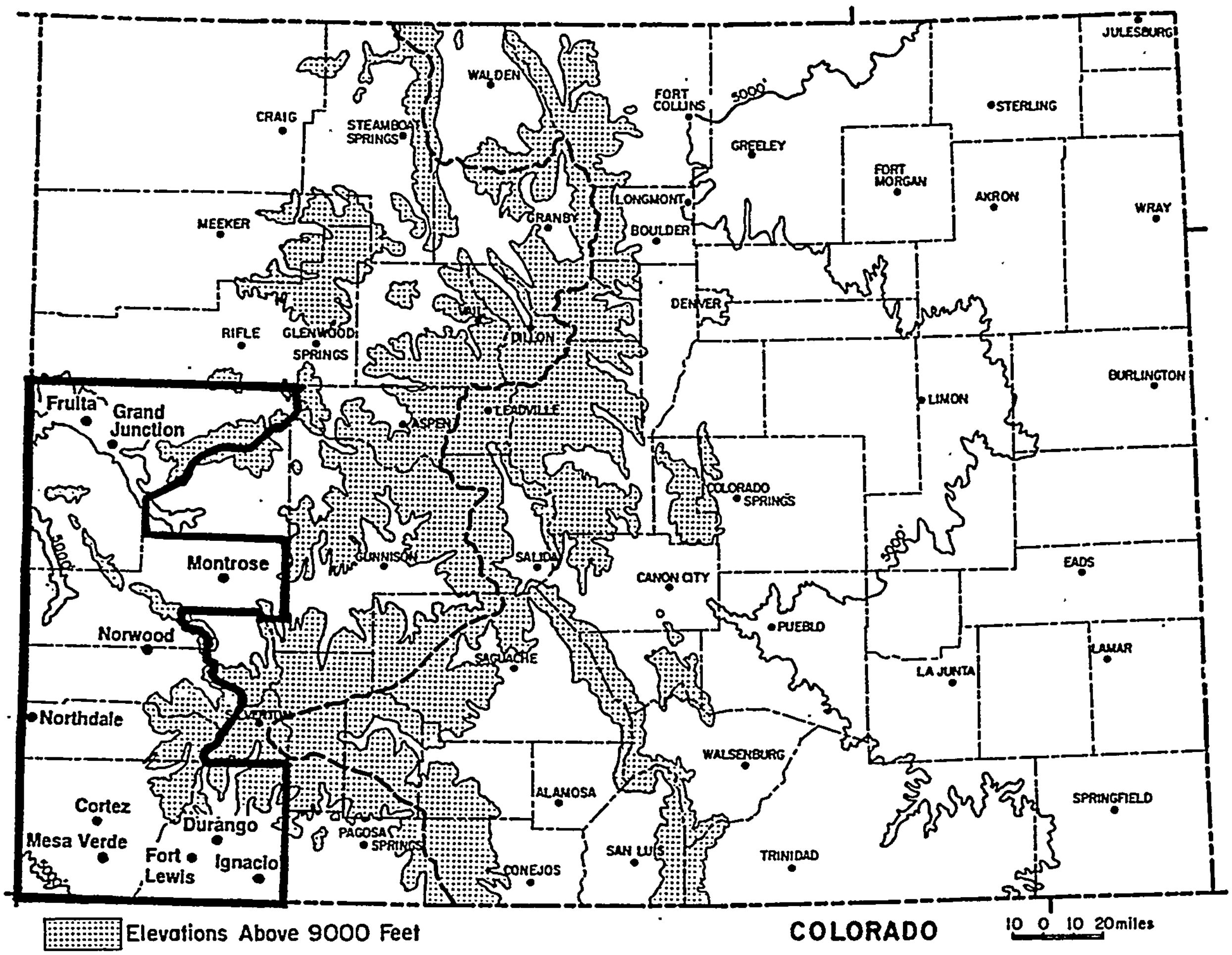


Figure 1. Map of Colorado showing general topographic features and county borders. The outlined area in southwestern Colorado includes the counties of Mesa, Montrose, San Miguel, Dolores, Montezuma, and La Plata. The National Weather Service long-term weather stations still collecting data in this region with at least 60 years of consistent climate monitoring are identified by name.

instruments and trained. Most weather stations were equipped with eight-inch diameter metal precipitation gages and self-registering liquid-in-glass maximum and minimum thermometers mounted inside wooden instrument shelters (National Weather Service 1989). Very few changes have been made in this network over the past century, and the data from the NWS cooperative network continues to be the best overall data source for climate monitoring in the U.S.

Figure 2 shows the number of weather stations that were operating as a function of time in the six-county area of southwestern Colorado since 1880 (Mesa, Montrose, San Miguel, Dolores, Montezuma and La Plata Counties). The number of stations increased significantly during the early 1900s but levelled off after 1960. Many stations have come and gone after collecting only a few years to a few decades of data. A total of 10 stations was identified with at least 60 consecutive years of complete data that continue to operate at the present time. Due to our primary interest in the Four Corners region, high elevation stations in the San Juan Mountains were not included. The ten stations are identified in

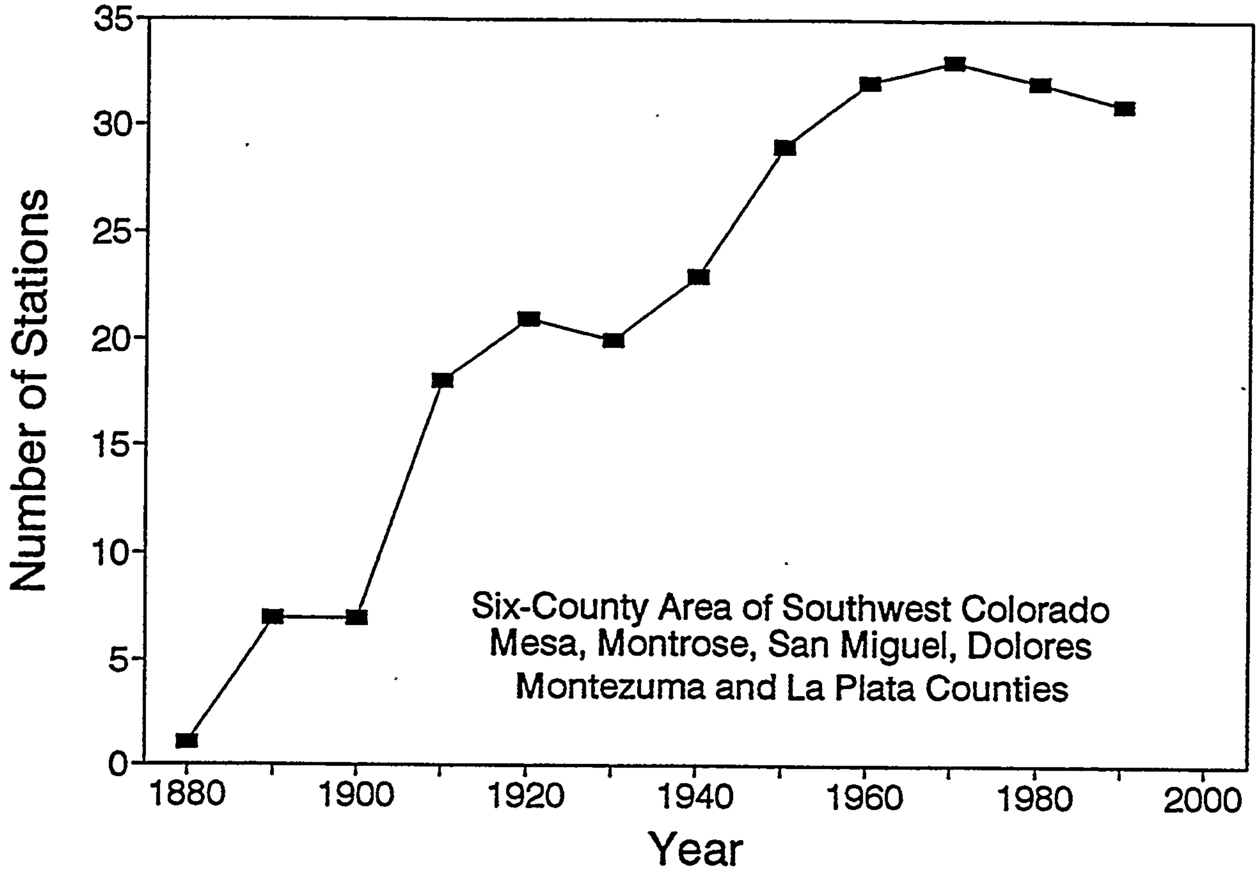


Figure 2. The number of officially documented National Weather Service weather stations in operation in southwestern Colorado (Mesa, Montrose, San Miguel, Dolores, Montezuma and La Plata Counties), 1880–1990.

Table 1 and their locations are shown on Figure 1. All analyses shown in the following sections are based on data from these long-term sites.

It is important to be aware of the fact that during the past 10 to 20 years many new sources of weather data have begun to appear in the Four Corners region. Dozens of remote automated weather stations can now be found operated by a variety of government and private sources. So far, data from automated stations are typically not collected for climate purposes and are often difficult for outside users to obtain. Instrumentation and data collection procedures are also not consistent. Therefore, we have not included these weather stations in this paper. In future decades, data from these sources may have an increasing role in evaluating climate variations and change.

PRESENT CLIMATIC CHARACTERISTICS

Data for the 31 year period, 1962–1992 were used to identify key features of the current climate of Southwest Colorado. The most consistent feature of the climate is the annual temperature cycle. Monthly averages of the daily maximum and minimum temperatures (Figure 3) show the traits common to the interior continental mid-latitude regions with

Table 1. Long-term National Weather Service climate stations in southwestern Colorado currently in operation and with at least 60 years of consistent data.

Station Name	Latitude	Longitude	Elevation (feet)	Number of Years of Record through 1992 for: Temperature	Number of Years of Record through 1992 for: Precipitation
Cortez	37°22′	108°33′	6212	64	64
Durango	37°17′	107°53′	6600	98	98
Fort Lewis	37°14′	108°03′	7600	86	92
Fruita	39°10′	108°45′	4480	94	94
Grand Junction	39°07′	108°32′	4842	101	101
Ignacio 1N	37°08′	107°38′	6460	79	79
Mesa Verde National Park	37°12′	108°29′	7115	70	70
Montrose	38°29′	107°53′	5785	91	105
Northdale	37°49′	109°02′	6680	63	63
Norwood	38°08′	108°17′	7020	62	62

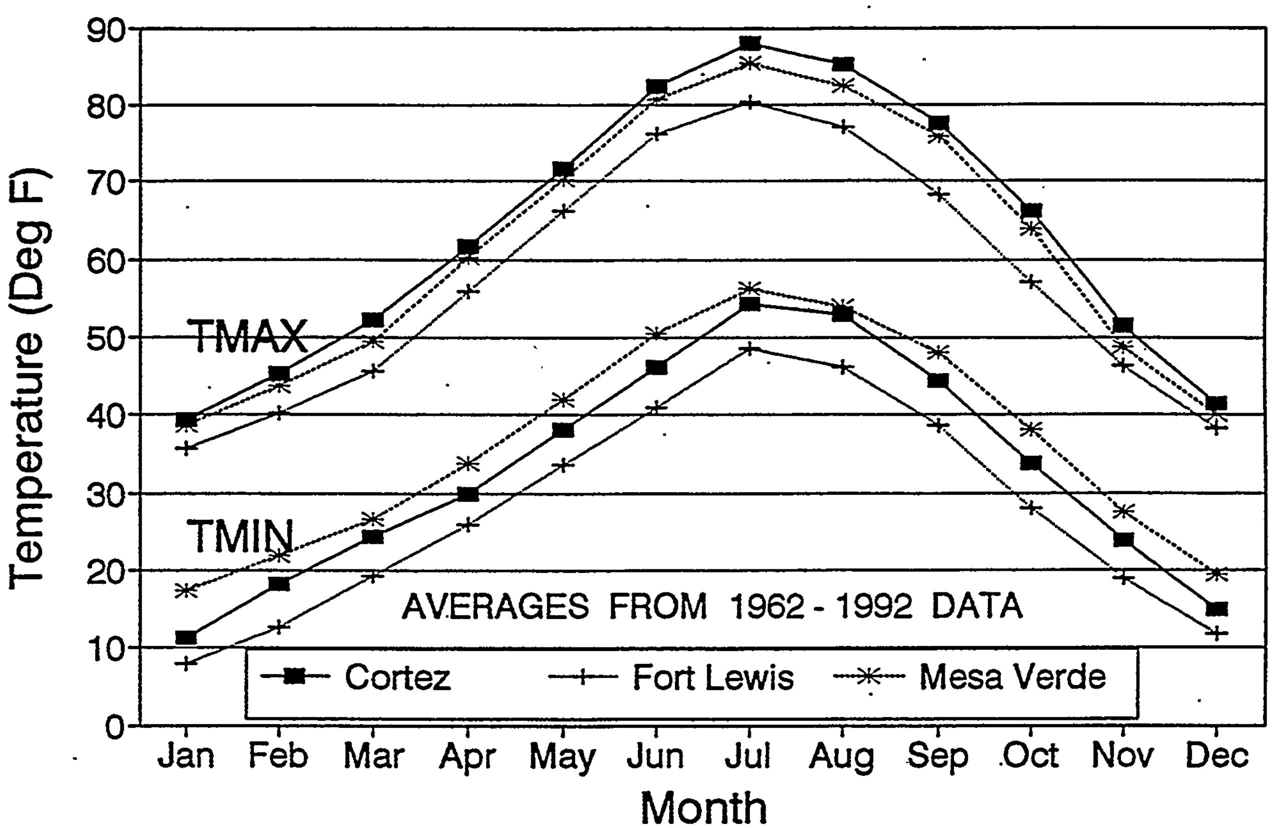


Figure 3. Average monthly maximum and minimum temperatures in degrees Fahrenheit for selected southwestern Colorado weather stations; Cortez, Fort Lewis and Mesa Verde; based on 1962–1992 data.

air temperatures lagging the annual solar cycle by a few weeks. On average, January is the coldest month of the year with daytime temperatures typically reaching into the 30s and 40s (degrees Fahrenheit) across the region and with nighttime temperatures averaging from the single digits to the low 20s. July is normally the warmest month of the year with highs typically in the 80s and 90s and with lows from the upper 40s to the 60s. More detail is shown in Figure 4 based on daily averages and extremes for Cortez and Mesa Verde. The annual temperature wave is close to sinusoidal but has a more gradual temperature rise in the spring and a more rapid decline in the autumn. Larger day-to-day variations in temperature occur in winter than in summer related to more frequent changes in air masses and cloud conditions. However, day-to-day temperature changes in the Four Corners area are not nearly as great as the variations observed east of the Rocky Mountains.

Mean monthly and annual temperatures generally decrease with altitude in this region (Figure 5), but local topographic effects related to cold air trapping and inversion formation affect this relationship. For example, much of Mesa Verde is unusually mild for its elevation. In general, temperature decreases with elevation are most consistent during the daytime and especially during the summer. The average July maximum temperature at Grand Junction (elevation 4842 feet) is 94° decreasing to 87° at Durango (6600 feet) and 81° at Fort Lewis (7600 feet).

A decrease of approximately 5 degrees Fahrenheit per one thousand feet is typical for summer days. Other factors besides elevation become increasingly important at night and especially during the winter.

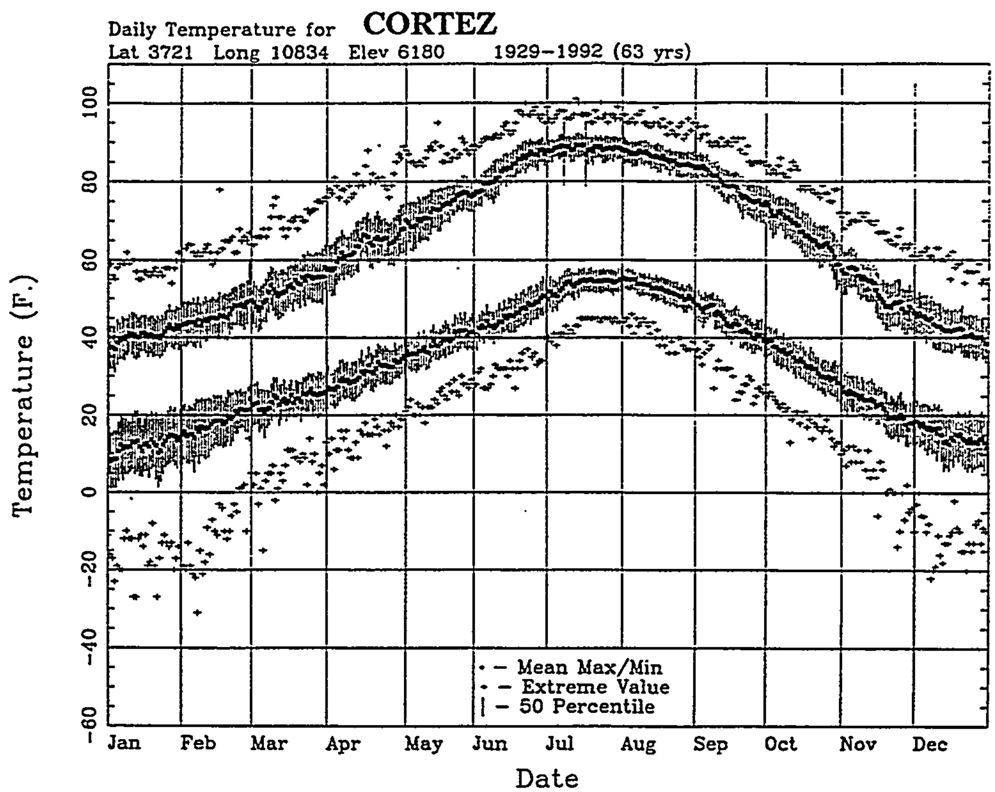
Diurnal temperature ranges (day-night temperature differences) are large throughout southwestern Colorado but show considerable local variations (Figure 6) based on topography. June has the largest day-night temperature differences while December typically has the least. The weather station on Mesa Verde has smaller diurnal ranges than any other reporting station in the region with day-night differences of only about 20 degrees Fahrenheit.

Average annual precipitation over Southwest Colorado ranges from less than eight inches near Grand Junction to more than 30 inches in the San Juan Mountains. Precipitation generally increases with elevation but elevation is not the only controlling variable. More than 75% of the annual precipitation falls as rain at lower elevations. Above about 8500 feet the majority falls as snow.

Precipitation patterns are much more complex and much less consistent year to year than temperature. There are three primary precipitation mechanisms influencing southwestern Colorado: 1) Large-scale cool season storm systems that approach from the Pacific (November–April) and are greatly enhanced by orographic lifting, 2) summer convective precipitation that becomes heaviest and most widespread when monsoon moisture spreads into the region from the south (early July–early September), and 3) autumn storm systems that combine tropical air masses and the remains of occasional Pacific hurricanes with early autumn mid-latitude storms. Each of these mechanisms operates nearly independently, although some connection to the Pacific El Nino circulation can be traced.

The resulting pattern of mean seasonal precipitation (Figure 7) shows a late summer and fall precipitation maximum at most sites. At the lower elevation sites near the Utah border, October is the wettest month of the year. This seasonal pattern is unique to the Colorado Plateau region. Winter maximums occur nearer the San Juan Mountains. Throughout the Four-Corners region, extremely dry Junes are a reliable feature of the climate.

Interannual precipitation variability is a key feature of the climate over southwestern Colorado and is greater in this region than in most of the rest of the Western U.S. (Changnon et al. 1991). It is very common to



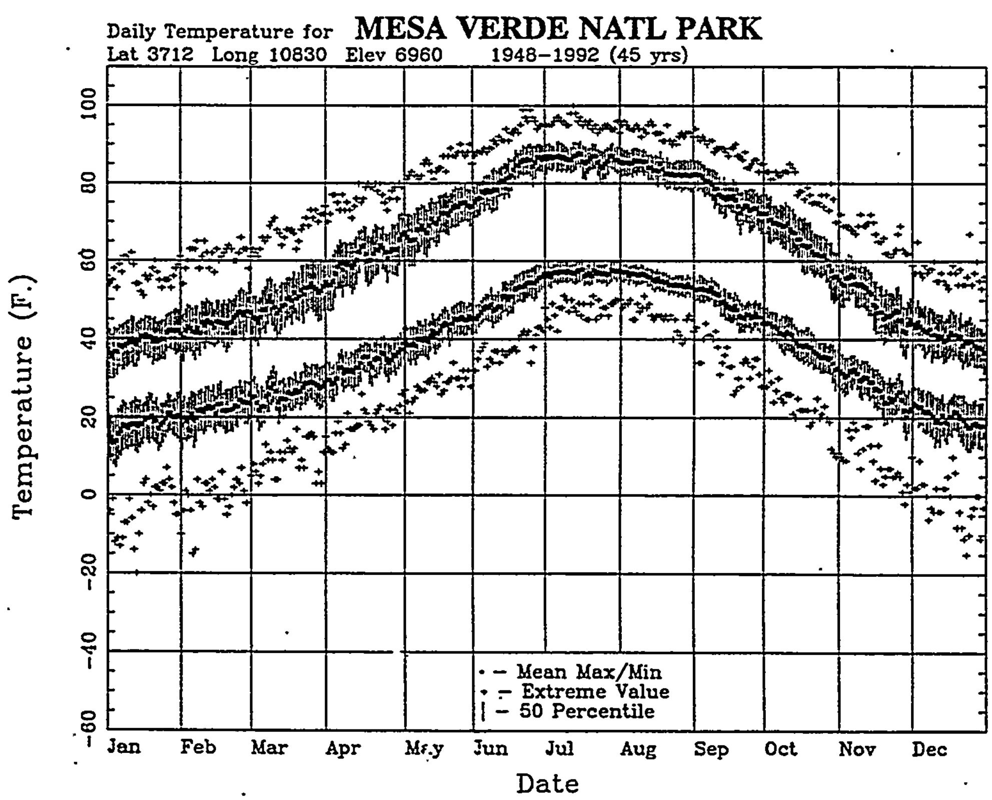


Figure 4. Average daily maximum and minimum temperatures, typical variability (vertical lines) and daily extremes for Cortez and Mesa Verde National Park.

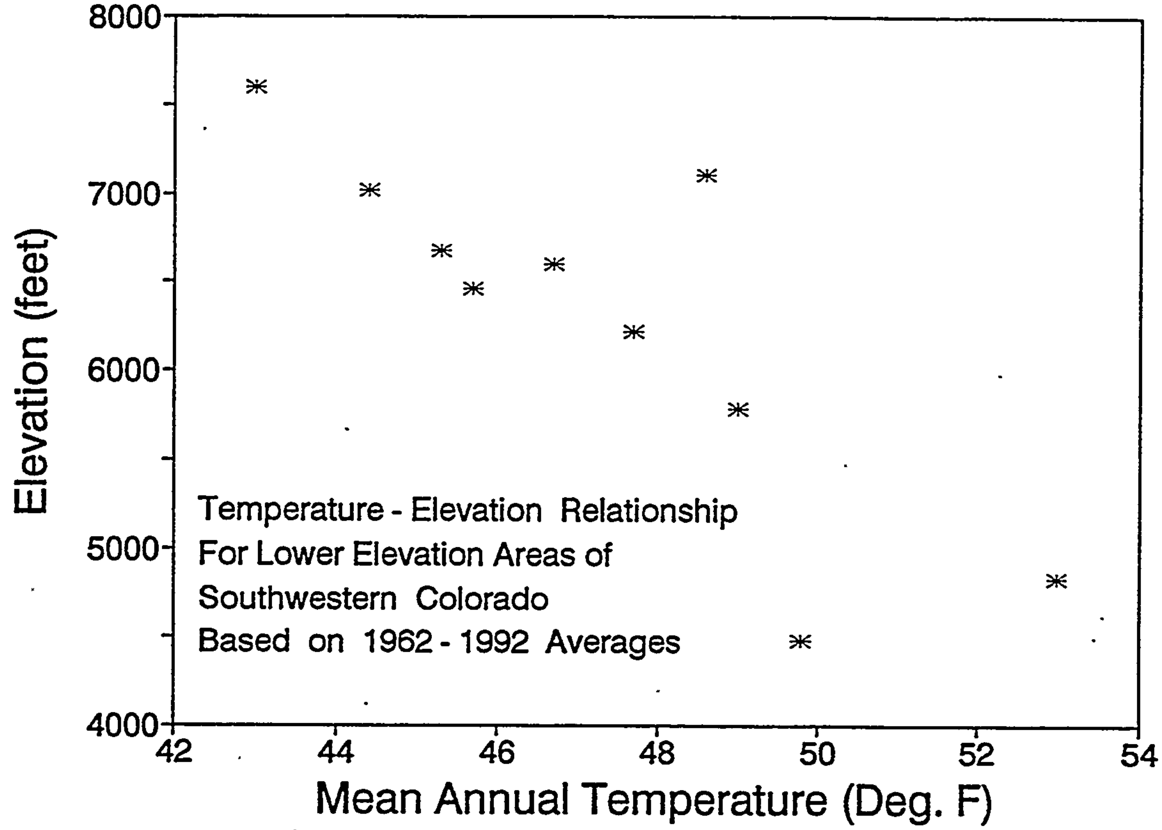


Figure 5. Mean annual temperature, based on 1962–1992 data, as a function of elevation for ten stations in southwestern Colorado with long-term climate records.

have alternating seasons and years with much above average and much below average precipitation. A large percentage of any year's precipitation falls from a small number of storms (typical for most arid and semiarid regions). A combination of factors related to being south of the primary winter mid-latitude storm track and on the north end of the summer and fall tropical moisture intrusions contribute to large variability. Distributions of monthly precipitation are typically skewed in all climates but especially in dry climates with highly variable precipitation. Figure 8 shows median versus mean precipitation for selected stations. For many purposes, the median provides a better description of the climate. Medians are less than means for all stations and for nearly all months. Median precipitation for a given month is typically about 10% less than the mean. However, means and medians are quite similar during July and August and tend to be the most different during September and October.

For many applications, the occurrences of intense rainfalls and flooding are of great importance. Based on data since 1962, the probabilities of receiving heavy rains in excess of one inch in less than 24 hours is far greater from late July into mid October than at any other time of year.

OBSERVED CLIMATE DIFFERENCES

With barely 100 years of instrumental observations at our disposal, interannual and interdecadal variations dominate the climate record and challenge any attempts at deducing long-term trends. Furthermore, superimposed on the actual climate signal are variations and discontinuities in the climate record resulting from any of several possible observational

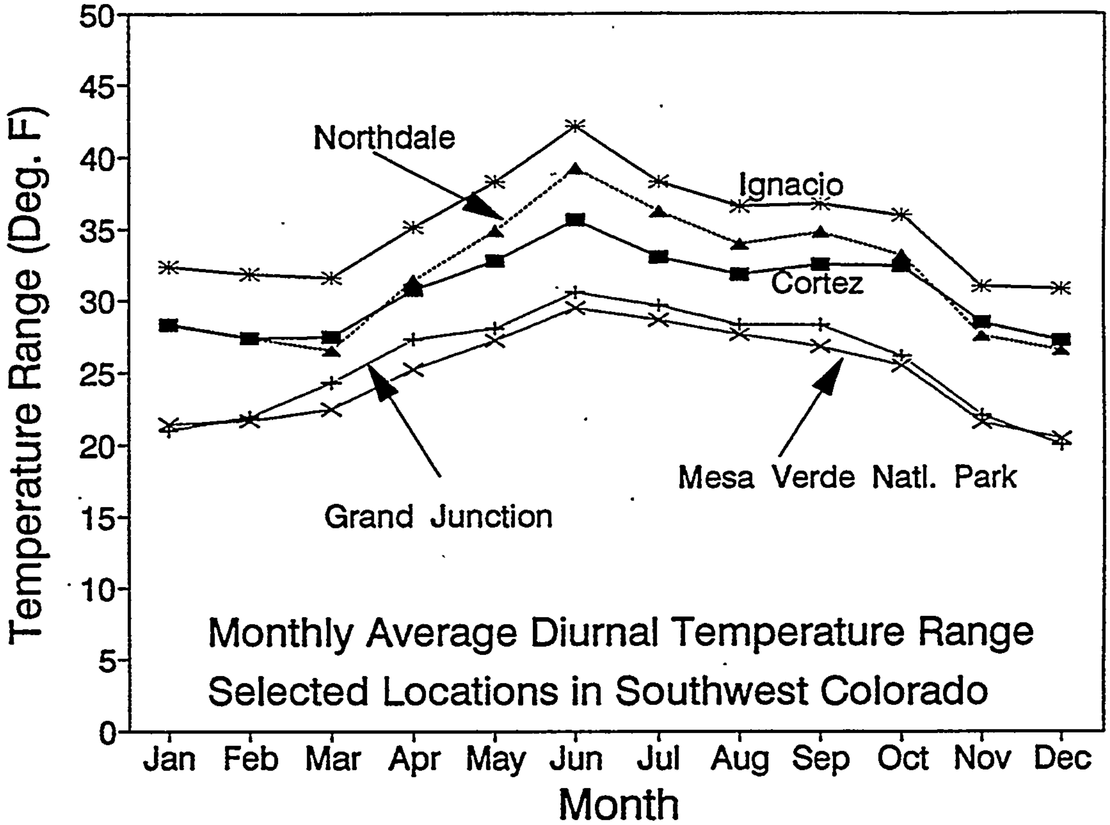


Figure 6. Monthly average diurnal temperature range (difference between the average daily maximum temperature and average daily minimum temperature), based on 1962–1992 data, for selected locations in southwestern Colorado.

issues. As such, we prefer to analyze "climate differences" rather than "climate change." To look at climate differences, the instrumental record was divided into three non-overlapping 31-year periods, 1895-1925, 1926-1956 and 1962-1992. These periods were chosen arbitrarily but consistent with available data. Thirty-one year periods are used, rather than the 30 year interval commonly used to establish climate normals, simply for convenience in determining median values.

Only three stations had complete data for all three periods, Grand Junction, Montrose and Durango. Figure 9 compares 31-year average monthly temperatures and precipitation for the three periods. Small but observable differences in 31-year monthly temperature averages can be seen at each station. At Grand Junction, for example, daily maximum temperatures in the past 31 years have been consistently higher than at any time previous for the months of May through October. Durango data show 1° to 2.5°F higher average maximum temperatures throughout the year than in the past. Neither station shows any significant change in average minimum temperatures. Montrose shows the greatest differences with minimum temperatures now warmer than they have been in the past. Montrose data reveal some surprisingly large differences between the 1895-1925 and the 1926-1956 periods. The 1962-1992 averages lie between the other periods. Temperatures at these three sites fail to show the consistent reduction in diurnal temperature range that has been noted for much of North America (Karl et al. 1986).

Not surprisingly, some significant differences in precipitation have been observed. For example, at Grand Junction, annual average precipitation decreased from the earliest period

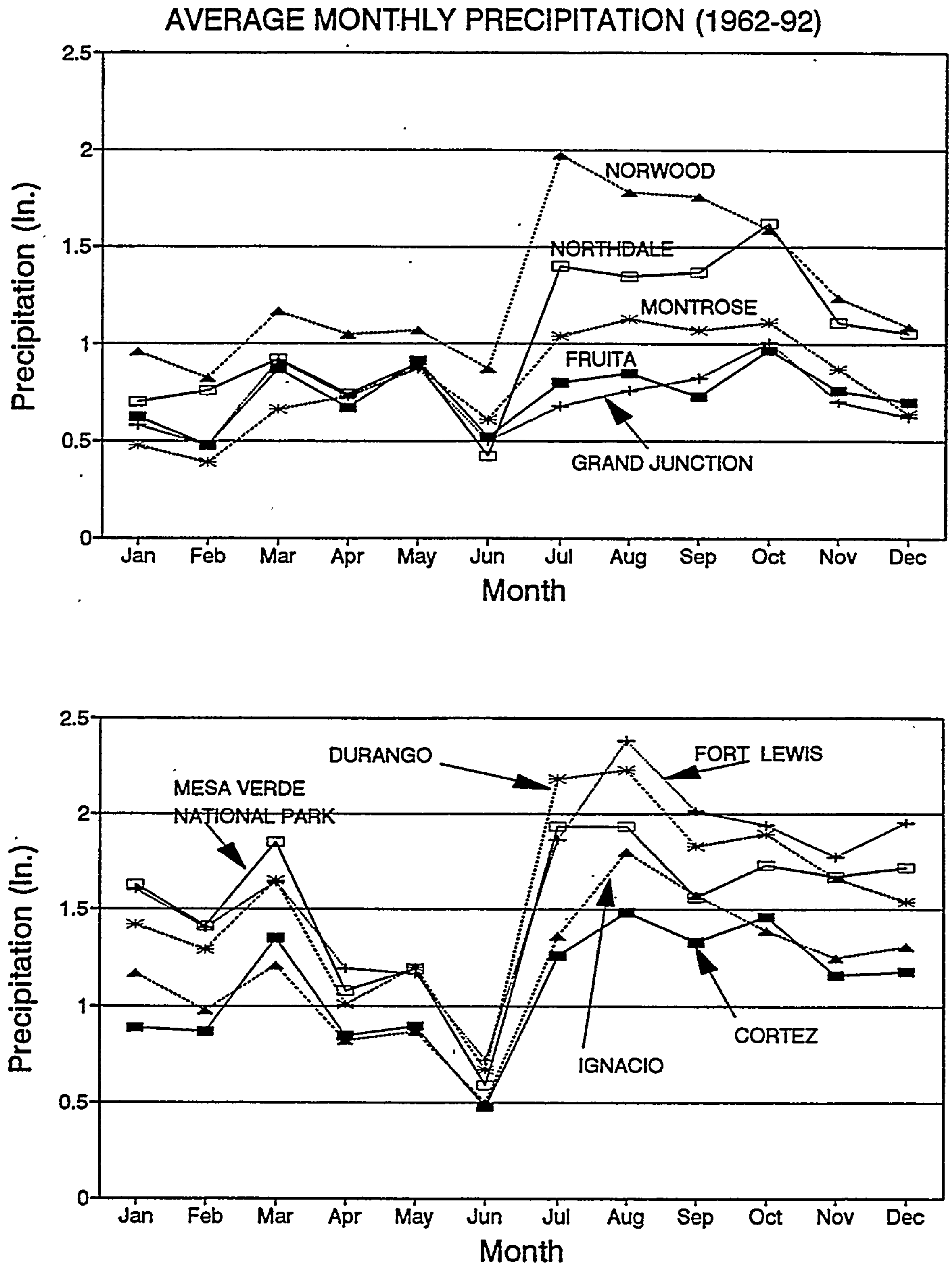


Figure 7. Average monthly precipitation in inches, based on 1962–1992 data, for each of the ten stations with long-term data in southwestern Colorado.

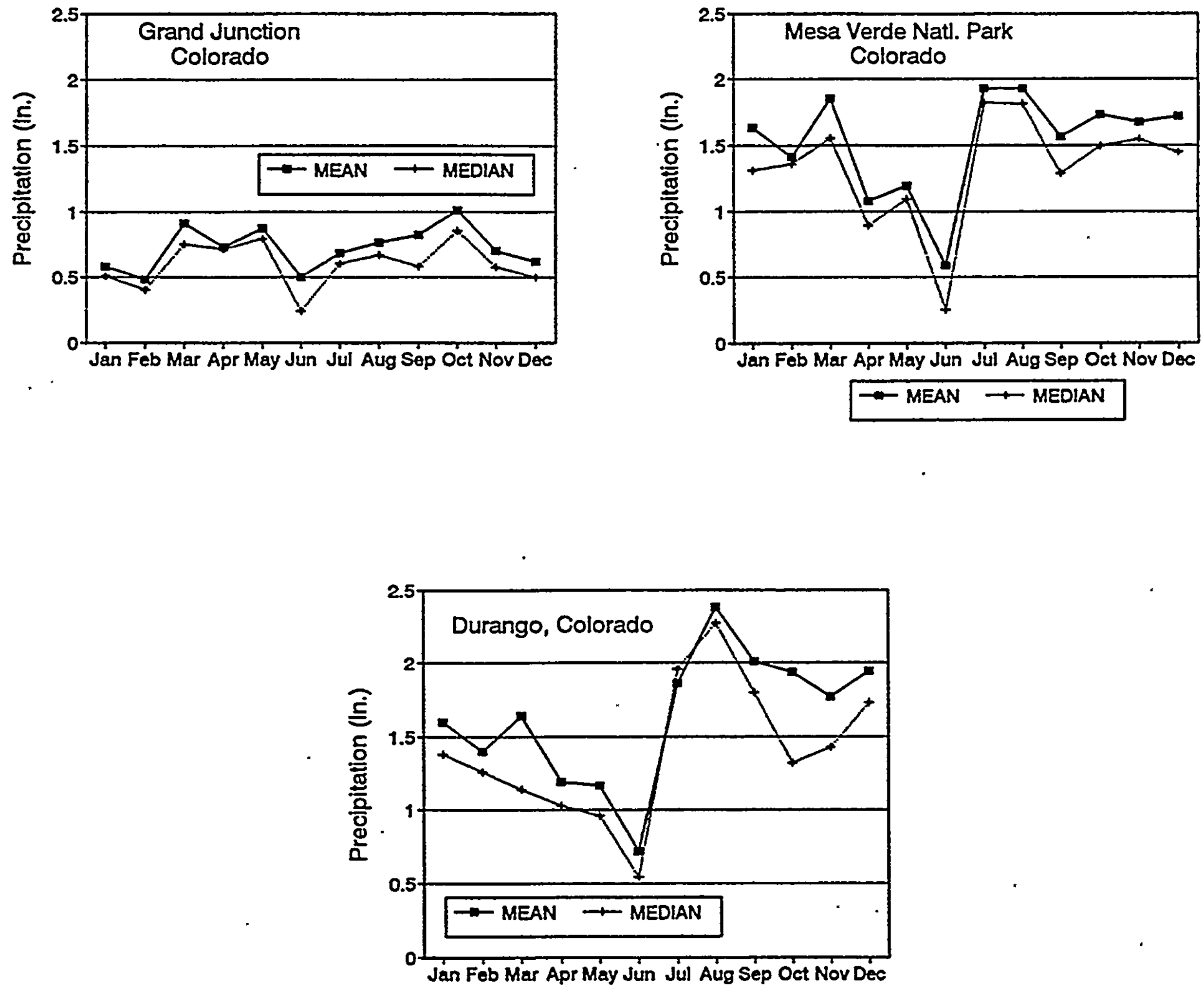


Figure 8. Comparison of monthly average precipitation and median precipitation based on 1962–1992 data for Grand Junction, Mesa Verde National Park and Durango, Colorado.

to the 1926-1956 period and then increased again in the most recent period. May has emerged as the most consistently wet month, nearly double the May values of the previous periods. At the same time, Grand Junction has seen a decrease in late summer precipitation but an increase in late fall moisture. Montrose shows some of the same features but with smaller overall changes. August and October have remained the wettest months of the year there. November precipitation has shown the largest increase. Finally, the Durango data show that the wettest period of the instrumental record was 1895-1925. That early period included wet early springs that have not been paralleled in subsequent years. The 1926-1956 period was the driest portion of the record. During that period, precipitation was significantly lower from late summer through early winter. The most recent period, 1962-1992, has been characterized by wet summers and wetter early winters (November-December) but drier springs than during any other portion of the instrumental record.

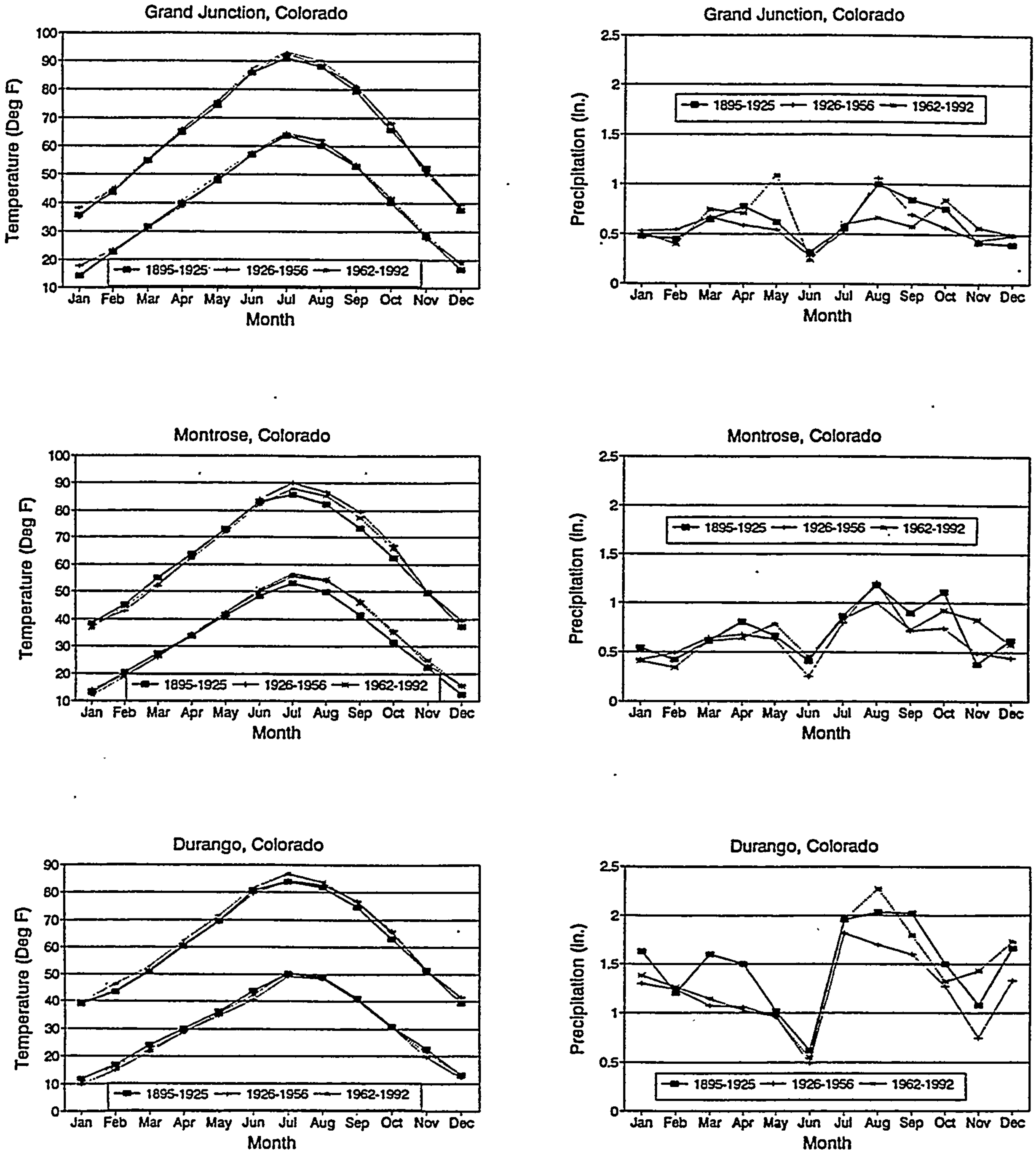


Figure 9. Comparison of 31-year average temperatures (left column) and 31-year median precipitation (right column) for three periods, 1895–1925, 1926–1956, and 1962–1992, for Grand Junction (top), Montrose (middle) and Durango, Colorado (bottom).

Changes in the seasonal distribution of precipitation, in combination with subtle temperature changes, could produce significant changes in the overall surface water balance of the region. A comparison of the seasonal distribution of precipitation at the Mesa Verde National Park long-term climate station for the 21 individual (not consecutive) wettest and driest years (based on calendar year totals) is shown in Figure 10. While the general seasonal distribution of precipitation has been similar between wet, dry and average years, the wettest years have been characterized by a higher percentage of the annual precipitation falling during the winter months.

Frequencies of heavy precipitation events and flooding were not included in this study. Instead, a time series of a drought monitoring index developed for Colorado (McKee et al. 1993) called the Standardized Precipitation Index (SPI) is shown in Figure 11. The SPI requires only monthly precipitation values for computation, but needs consistent and long-term data. Index values of -1 or lower represent periods of drought while periods above +1 are very wet. There are many differences in the SPI time series between Grand Junction, Montrose, and Durango, but the three stations share most of the very dry and very wet periods in common. Overall, the worst drought period took place from 1899–1903. There was almost no drought from then until the early 1930s. There have been several occurrences of drought since 1950, but all have been short in duration, including the severe drought of 1976–77. The wettest period in the record for Grand Junction and Montrose took place from 1983 to 1987.

The type of information from Figure 11 is very helpful in explaining typical characteristics of drought and precipitation variability. However, even with 100 years of consistent data, it is impossible to confidently assess probabilities for long-duration severe wet or dry episodes.

WEAKNESSES OF THE INSTRUMENTAL CLIMATE RECORDS

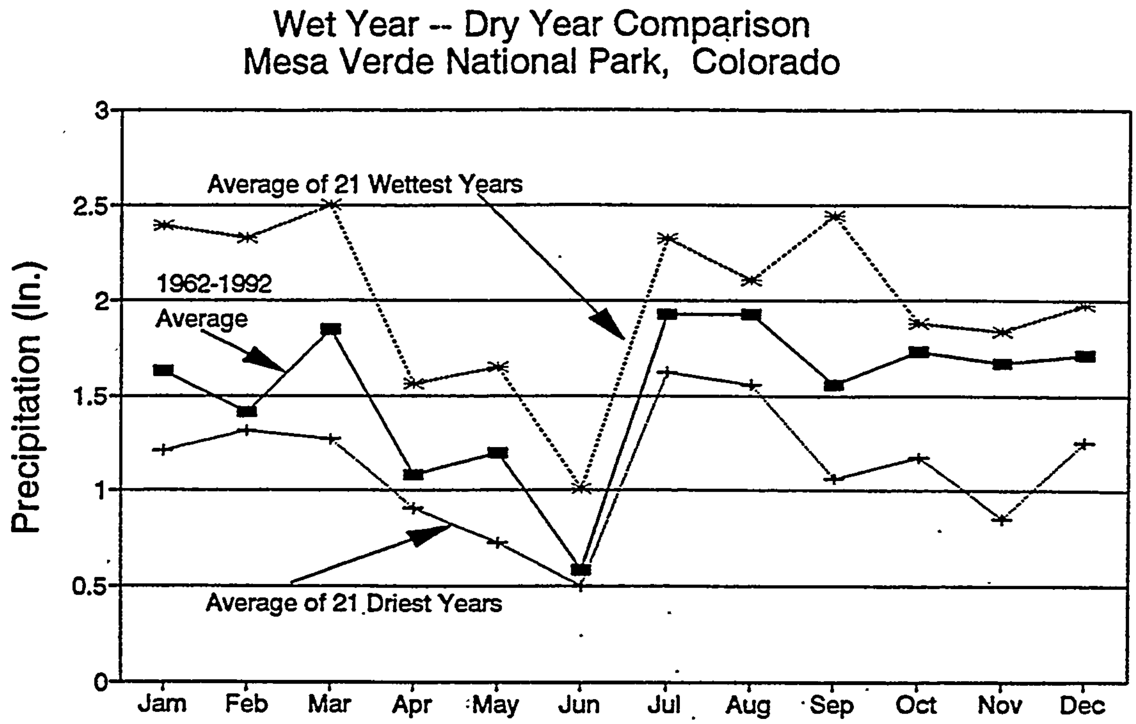
There is a tendency to accept instrumental climate records as absolute truth and draw conclusions accordingly. For many applications, the accuracy of basic temperature and precipitation data is more than adequate. However, when attempting to detect subtle climate differences over time, weaknesses in the observations become very significant.

There are seven main factors that introduce inconsistencies into the instrumental climate record:

1) incomplete records and missing data,
2) station moves,
3) observer changes (with or without station moves),
4) observation time changes,
5) exposure changes (gradual or instantaneous),
6) instrument changes,
7) urban heat island biases.

In addition to these seven, changes in the number and location of stations within a larger region can greatly alter regional averages computed from all available data.

Much has been and could be written on these topics and need not be repeated here. However, it is important to know, for anyone using instrumental climate records, that any of these factors have the potential of introducing "differences" into the climate record. To a varying extent, all of these factors influence the instrumental climate record of all of the U.S. including southwestern Colorado. Temperature changes associated with station moves, exposure changes and observation times are typically on the order of 1° to 4°F. Instrument changes alone usually result in changes of no more than about 1°F. Urban heat island biases usual develop gradually but can result in changes of several degrees over a



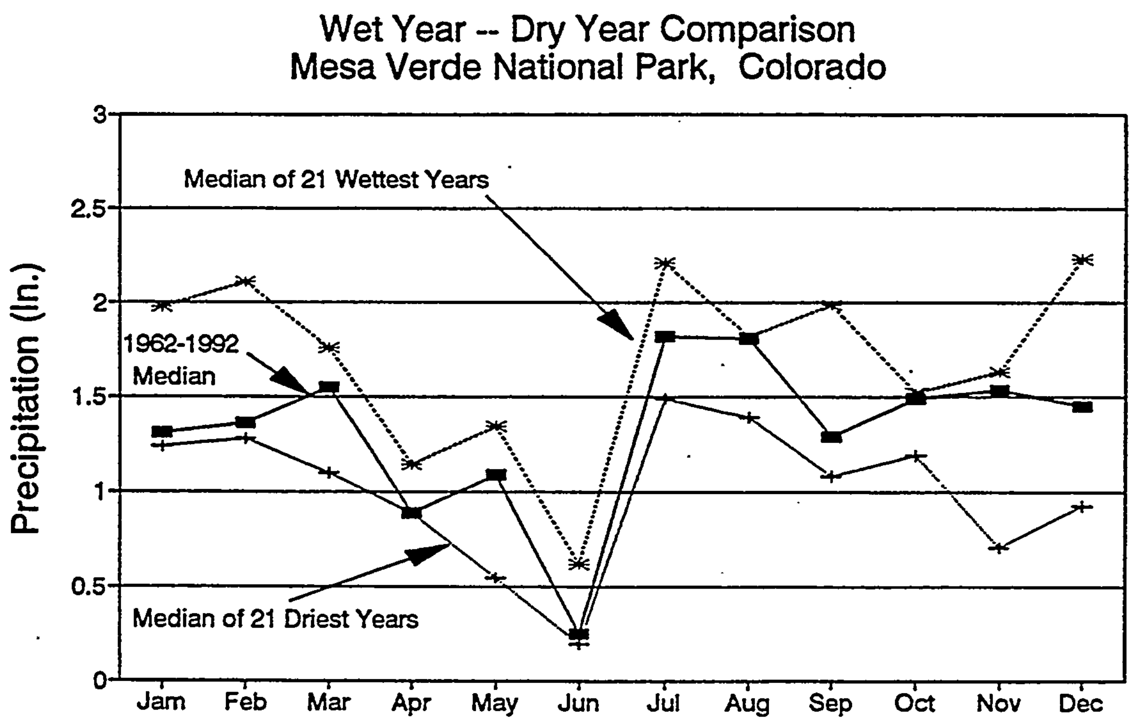


Figure 10. Comparison of monthly average precipitation (top) and median precipitation (bottom) for Mesa Verde National Park for the 21 wettest and 21 driest calendar years with the 1962–1992 precipitation.

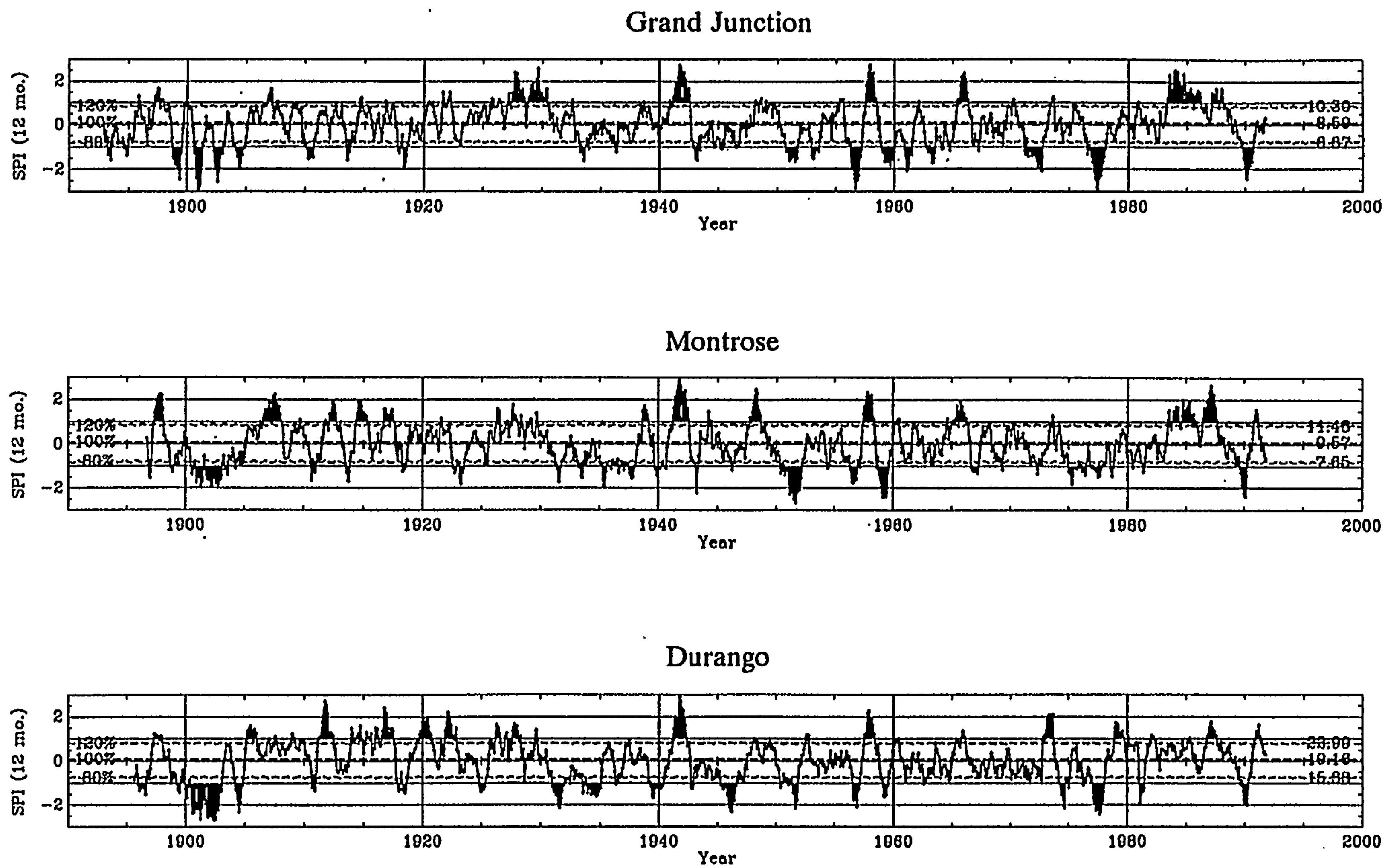


Figure 11. Time series of the Standardized Precipitation Index (SPI) computed for consecutive overlapping 12-month periods for Grand Junction, Montrose and Durango, Colorado.

few decades. Hence, the differences that have been observed through the period of instrumental record are of the same magnitude that can be artificially introduced by station changes.

The same is true with precipitation. Precipitation measurements are especially sensitive to location and exposure changes. These can account for precipitation differences for monthly and annual totals of as much as 10-30%, particularly in areas that receive a significant portion of their annual precipitation as snow.

The instrumental record provides great detail for describing our climate. It is the responsibility of the scientist, however, to become very familiar with individual station histories before drawing too many conclusions regarding "apparent" long-term climate changes.

CONCLUSIONS

The instrumental record for southwestern Colorado dates back just over 100 years. Only ten stations exist with at least 60 consecutive years of temperature and precipitation data. The data resources are sufficient, however, to define many aspects of the climate of the Four Corners area. Minor temperature differences have been observed from the earliest instrumental records until the present. Most areas show slightly warmer temperatures now than at the beginning of the 20th Century, but with little change in the shape of the annual cycle. In terms of precipitation, southwestern Colorado experiences large interannual variations which, in turn, have introduced considerable variations in monthly averages over longer time periods. The wettest periods in the region occurred from approximately 1904 to about 1930 and during the mid 1980s. Drought was most prevalent 1889-1903 and sporadically but with short duration since the 1930s. Some differences in the seasonal pattern of average precipitation across the region have been observed from the early record until the present.

The instrumental record offers a wonderful resource for evaluating the climate. Data users must be aware, however, that instrumental observations do not provide the absolute truth but simply a reasonable representation of the truth. With a relatively small commitment of time and resources, it should be possible to continue and improve consistent instrumental climate monitoring into the future. Every effort should be made to make sure climate monitoring continues.

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Session IV: Climate Change, Ecological Resources, and Environmental Restoration

IMPACTS OF CLIMATE CHANGE ON NUTRIENT CYCLING IN SEMI-ARID AND ARID ECOSYSTEMS

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National Biological Survey

ABSTRACT

Effective precipitation is a major factor in determining nutrient pathways in different ecosystems. Soil flora and fauna play a critical role in nutrient cycles of all ecosystems. Temperature, timing, and amounts of precipitation affect population composition, activity levels, biomass, and recovery rates from disturbance. Changes in these variables can result in very different inputs and outputs for different nutrients. As a result, areas with less effective precipitation have very different nutrient cycles than more mesic zones. Climate change, therefore, can profoundly affect the nutrient cycles of ecosystems.

Nitrogen cycles may be especially sensitive to changes in temperature and to timing and amounts of precipitation. Rainfall contains varying amounts of nitrogen compounds. Changes in amounts of rainfall will change amounts of nitrogen available to these systems. Because rainfall is limited in semi-arid and arid regions, these systems tend to be more dependent on microbial populations for nitrogen input. Consequently, understanding the effects of climate change on these organisms is critical in understanding the overall effect on ecosystems.

THROUGH A MIRROR, DARKLY—
USING CLIMATE CHANGE INFORMATION FOR LAND MANAGEMENT

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Keywords: *climate, climate change, ecology, ecosystem, ecosystem management*

ABSTRACT

The writer Bruce Hutchison uses the phrase: "The land, always the land!"

The land is a common denominator linking the ages. But the "land" in the broadest sense is a vast collection of natural components, events, and interconnections. It is complex, only partially understood, and ever-changing.

Our ultimate challenge at this time is to SEE, as we look into the mirror of time. Regardless of the shadows of uncertainty, we must peer hopefully into the mirror to make meaningful connections between the past, the present, and the future. This is not easy.

Traditional resource planning has been based on the short-term focus of today and tomorrow. That focus is beginning to change through a concept now popularized as "ecosystem management." BLM recently has begun applying this concept in the formulation of the Eastern Utah Ecosystem Planning Initiative that is intended to give expanded dimensions to the planning and management of public land resources.

These dimensions will give more attention to spatial (regional) and temporal (long-term) expectations.

This paper investigates the theoretical and practical problems in linking the past to the future, using as the example the new planning initiative for Eastern Utah. It provides insights which may be applied to land-use planning and management, through new perspectives regarding changing climate and ecosystem patterns.

INTRODUCTION

There is a certain mind-tune or catchiness to the phrase: "The land, always the land!" (Hutchison 1967).

The land is a common denominator linking the ages. But the "land" in the broadest sense is a vast collection of natural components, events, and interconnections. It is complex, only partially understood, and ever-changing.

Weather and climate factors are taken into account by land management agencies during technical applications such as seedings, fires, and engineering design (NARTC 1994). However, climate considerations can be almost overlooked in broader aspects of planning and decision-making. In many planning actions climate may be taken as a given and passed over lightly; but in truth there is great difficultly in separating climate from the other aspects of the environment. The concept of significant climate change adds markedly greater dimensions to traditional land management.

To consider climate-related factors in the broadest sense, our ultimate challenge at this time is to *see*, as we look into the mirror of time. Regardless of the shadows of uncertainty, we must peer hopefully into the mirror to make meaningful connections between the past, the present, and the future. This is not easy.

Traditional resource planning has been based on the short-term focus of today and tomorrow. But philosophical changes are coming through a concept now popularized as ecosystem management (BLM 1994a). The Bureau of Land Management (BLM) recently has begun applying this concept in the formulation of the Eastern Utah Ecosystem Planning Initiative, intended to give expanded dimensions to the planning and management of public land resources. These dimensions will give more attention to spatial (regional) and temporal (long-term) expectations.

This paper weaves bits of information from the past, the present, and perhaps the future. It poses questions to stimulate thinking. Hopefully, it provides insights which may be applied to resource planning and management through new perspectives regarding changing climate and ecosystem patterns.

WHAT DO WE KNOW ABOUT CLIMATE CHANGE ON THE COLORADO PLATEAU?

Simply put, we know that long-term cool and warm weather cycles have occurred and that conditions today are much drier than at some periods in the distant past. Also we know the general geologic formation and the current residual erosional configuration. We know that certain stratigraphic geological layers contain significant fossil remains of plant and animal species; but even so, these fossil traces provide a spotty record. We presume that a number of species from the late-Pleistocene and Holocene fossil record are also within the active ecosystems of today (Neilson 1987).

Some of our knowledge comes from interpretation of physical objects or "nature's time capsules" (Stolzenburg 1994), such as tree rings, soil horizons, and dating of organic profiles. Clues can be found in ancient packrat middens and archeological sites. For example, through growth-ring analysis of roof beams, we know that Moon House at Cedar Mesa was constructed and occupied about A.D. 1265 (Bloomer 1988). And from packrat collections we might conclude that the Anasazi at Chaco Canyon "clear cut themselves out of house and home" (Stolzenburg 1994).

Only in the past 150 years or less have we directly observed and recorded historic information, such as pioneer journal observations, a random assortment of old photographs, measured climate records, and stream gauge readings. In terms of the paleoclimate timeline, this recent or hard information is merely a speck in time—but it is the basis for most traditional land management decisions.

Globally we know that a period called the "little ice age" occurred from about 1400 to the mid-1800s (Neilson 1987) and perhaps shaped to a great extent the conditions found by the early Europeans who came to the American West. For example, an 1848 diary of a traveler on the old Spanish Trail called the San Rafael "a fine stream and the best grass we have found since leaving Santa Fe" (Hafen and Hafen 1954). Given some consideration of a gradually warming and drying climate change in the region (Hadley et al. 1993), it could be speculated that lush grassy conditions at such sites may not be naturally possible to the same extent today, regardless of human land use and management actions. At other spots, earliest described conditions may not differ much from today, such as a Canyonlands location described by Newberry of the 1859 Macomb Expedition: "A few pinion and cedars cling to the sides and crown of the summits of the walls, while scattered cottonwoods and thickets of willow, with here and there a small tree of a new and peculiar species of ash, form a narrow thread of vegetation along its bottom" (Barnes 1988).

On the other hand, the current theories on the causes of migrational advances in pinyon-juniper woodlands include fire suppression, overgrazing, and, to a lesser extent, climatic change (Neilson 1987). "We cannot always distinguish between the results of man's actions and the effects of purely geological or cosmical causes" (Marsh 1882).

Within the long-term trends can be found small cycles of wet and dry periods, perhaps illustrated most graphically by stream chartings such as for Mill Creek, near Moab, Utah. See Figure 1.

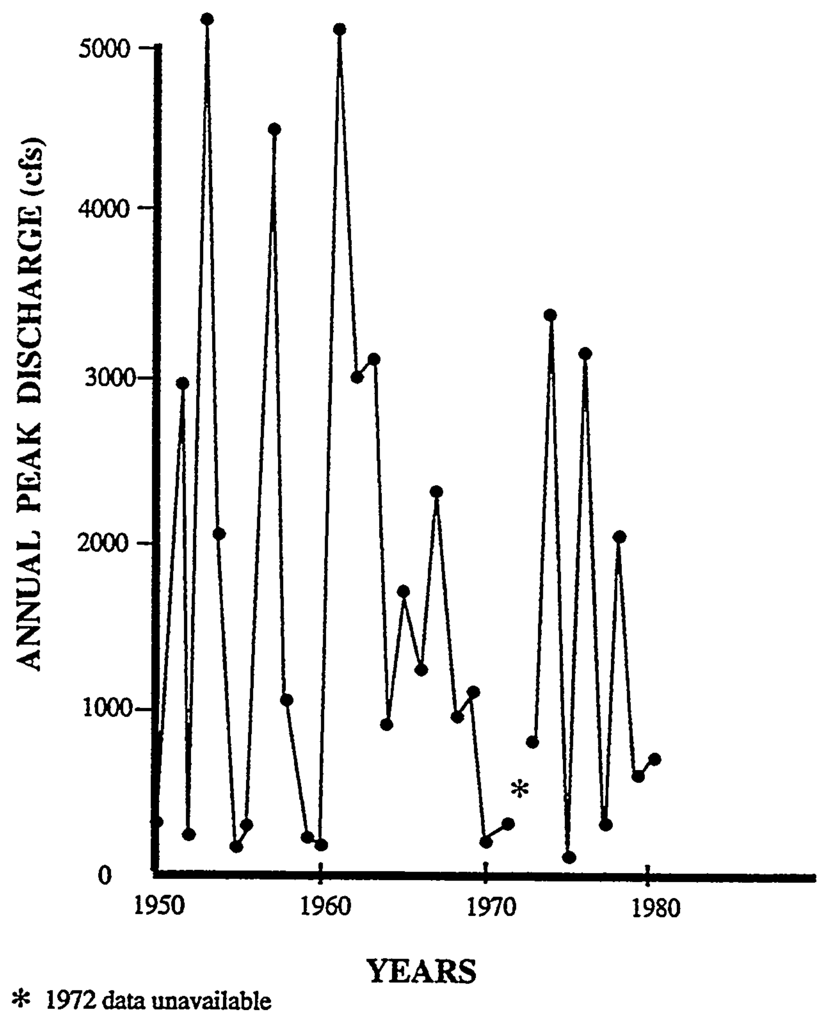


Figure 1. Example of Recorded Natural Variation, illustrated by the annual peak streamflow of Mill Creek near Moab, Utah. No storage projects or diversions influence the data set for this 30-year period (data from DOI, USGS 1987).

In many cases, user expectations and land-management practices (such as desired big game numbers and livestock grazing allocations) have focused intently on averages or maximums rather than the cyclic seasonal and yearly variations. Water storage projects, plantings, and other techniques have been pursued to stabilize consumptive use at high levels. Any deviation from this high norm at times has been considered a user hardship or an emergency rather than a natural phenomenon. In the American West, there is no truth to the idea that "rain follows the plow" (Stegner 1954).

A look at the timber harvest "targets" of recent years has given resource managers and others a hard lesson on the need to fit today's management and removal of products to the long-term variability patterns and productivity limits, taking into account natural ecological actions, past alterations by Native Americans, and the application of good scientifically based resource-management policies and practices (Peterson 1994). This issue is also a function of changing public values.

We have found that short-term economic gains which push natural resources to extremes often greatly diminish long-term ecological functions. Further, climate change itself can reduce economic opportunities, for example, by creating water stress at the margins of current forests, thereby creating management and timber-supply constraints. Global warming, as projected, could reduce income from timber sales by 26 percent in the western United States by the year 2030 (Regens et al. 1989).

In the face of perceived public needs, political demands, and limited information, public land managers for the past 75 years or so have been practicing "the art of the possible." The best knowledge, educated guesses, and intuition have been put in practice. Some things worked—some did not—and results of some still are unknown and may always be so. Even with a time span as short as 75 years, it is difficult to measure, understand, and manage for meaningful trends or purposeful ecological responses. This understanding is intellectually difficult, as well as constrained by limited funding and a shortage of people in the managing agencies. Nonetheless, practice and experience (learn as we go) counts fairly high in the collection of knowledge about resource management in the Colorado Plateau country.

Since 1910, the world's surface temperature readings have climbed about 2 degrees, with the peak reached in 1990. After a slight 2-year dip, the worldwide temperatures in 1993 climbed a bit, and some research meteorologists are wondering if the 83-year warming trend will ever reverse (Kirkman 1994). Also, 1994 was hot and dry. Now land managers on the Colorado Plateau and elsewhere in the Western United States are concerned with a marked period of drought, which began in the mid-1980s. "If current trends continue, the atmosphere will warm by about 1.5 to 4.5 degrees Centigrade by the year 2030. Warming of just 2 degrees Centigrade will take the earth out of the range of anything that has been experienced in the last ten million years" (Mintzer 1988).

HOW CAN THIS KNOWLEDGE BE USED IN CURRENT AND FUTURE LAND MANAGEMENT?

Information can be sorted in a variety of packages ranging from (1) macro to micro scales, (2) general to precise accuracy, (3) specialized to interdisciplinary focus, and (4) critical (essential) to marginal (nice-to-know). In daily resource management, the questions pertaining to knowledge continually arise—How accurate? How much value or usefulness? How much data are really needed? How do we know?

Among technical and scientific interests, the words ecology and ecosystem are not new. Recent discovery of these words is occurring in the public arena. As the business of public land management gives increasing attention to the popularized concepts of ecosystem management, the nature of required knowledge is changing. The traditional questions remain, but linkages and time lines are getting greater attention. Key to any current resource discussion is the word system. Some of the emerging questions are—What is the range of natural variability? What and where are the macro and micro climates? What are the long-term or cyclic trends (weather, hydrologic, vegetative, etc.)? What and where are the patterns —the cause and effect relationships? Where are the key nodes of biological diversity? What are the indicator species? (BLM 1994b).

These are difficult questions, for which answers may never be fully attained.

Situations with incomplete or unavailable information are addressed in the procedures for preparing Environmental Impact Statements, for compliance with the National Environmental Policy Act (NEPA). If relevant unknowns exist, steps to overcome this are: (1) make clear that information is incomplete or lacking, (2) identify the relevance (significance to the decisions under consideration) of the missing information, (3) summarize existing credible scientific evidence which may be useful to a reasoned process, and (4) evaluate impacts based on theoretical approaches or generally accepted research methods, using a reasonably-foreseeable scenario (Council on Environmental Quality 1986).

Since the World Commission on Environment and Development issued its report *Our Common Future*, the need for sustainability has gained tremendous support as an essential objective, worldwide (Brundtland 1987). The far-reaching work of the Commission covers the entire political agenda, but the document ultimately focuses on the current need to balance human life and wild land attributes at sustainable levels in developing countries, which comprise crisis conditions at this time. Nonetheless, there are related messages which come to mind—What is the concept of sustainability in the long term or very long term? Within a range of variability? In the context of biodiversity? Regarding extinctions?

Scholars have charted increased biodiversity over geologic time (Wilson 1988; Crowley and North 1988). The increasing trend has been interrupted with five great extinctions in the past (all earthbuilding or climate-induced), and a sixth (primarily human-induced) extinction is under way (Wilson 1992). (See Figure 2.)

On the same topic, a National Geographic Magazine article provides these clear and simple words:

> Whether or not we fit a cosmic timetable for an extinction, we surely are in one today.
>
> It began in North America about 11,000 years ago. Most large mammals were wiped out. Saber-toothed cats, mastodons, mammoths, huge ground sloths, short-faced bears, and dire wolves. All perished abruptly. What happened?
>
> Some scientists argue that the climate grew dryer. In western North America arid conditions dried up the food supply of large herbivores. As the herbivores disappeared, so did the carnivores that preyed on them.
>
> The extinctions, however, were so rapid—within five hundred to a thousand years—that many scientists suspect an alternate—or at least an assistant—villain in this extinction: Homo sapiens. Man the hunter emerged from the Ice Age with lethal new hunting technologies—snares, traps, and sharp-pointed weapons.
>
> Today the impact of human technology on the biosphere worsens. It exterminates not just the big creatures but the tiny (Gore 1989).

So we come to the bottom line—How to manage resources, habitats, and species sustainably on a day-to-day basis as well as with a five hundred to a thousand year (or more) perspective—in both crisis conditions and for the long term—with multiple agencies—against a

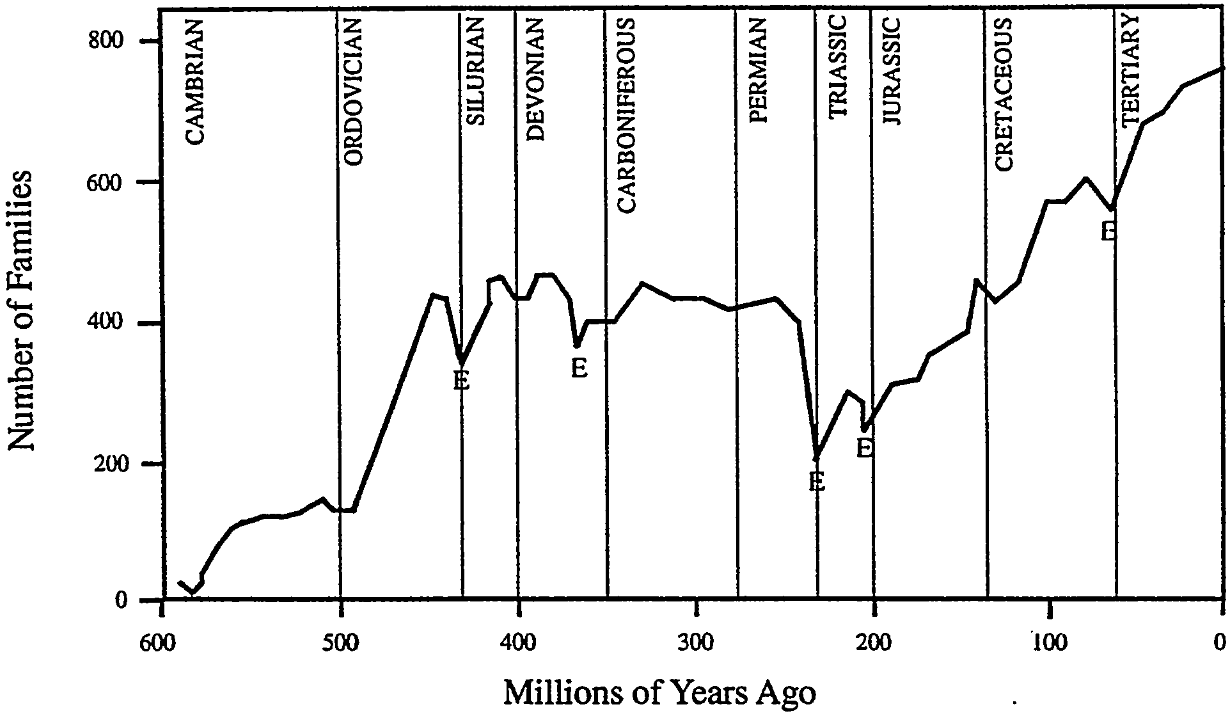


Figure 2. Biodiversity Patterns and Extinctions. Biological diversity has increased slowly over geological time. Five mass global extinctions have been detected, shown by E. Data are for families of marine organisms. (Adapted from Wilson 1992)

background of incomplete information, with politics and public processes, legal mandates, individual and public perceptions, local and national agendas, built-in desires to do good (however defined differently by each individual or social group)—and matching expectations with the realities that the future climatic regime (albeit difficult to see) will allow.

The lens with which to *see* the past, the present, and the future is now called ecosystem management, an integration of ecological, economic, and social principles (BLM 1994a).

General attributes are shown in Figure 3. Perhaps at the philosophical level and on the regional scale are where a better understanding of long-term climatic changes may best contribute to planning and conducting land/resource management actions. At the same time, it is granted that paleo and archeological data usually are obtained site-by-site and bit-by-bit. Aggregation of this data, interpolation, modeling, a sprinkle of "guesstimation," and the ability to see through the mirror (however darkly) of time are essential to make good use of such information. See Figure 4.

EXPLORING FRESH PROSPECTS—THE EASTERN UTAH ECOSYSTEM PLANNING INITIATIVE

Traditional resource planning has been done according to administrative boundaries that have little or no relationship to resource patterns. Now measures are under way in many places across the West to change planning to fit resource considerations better.

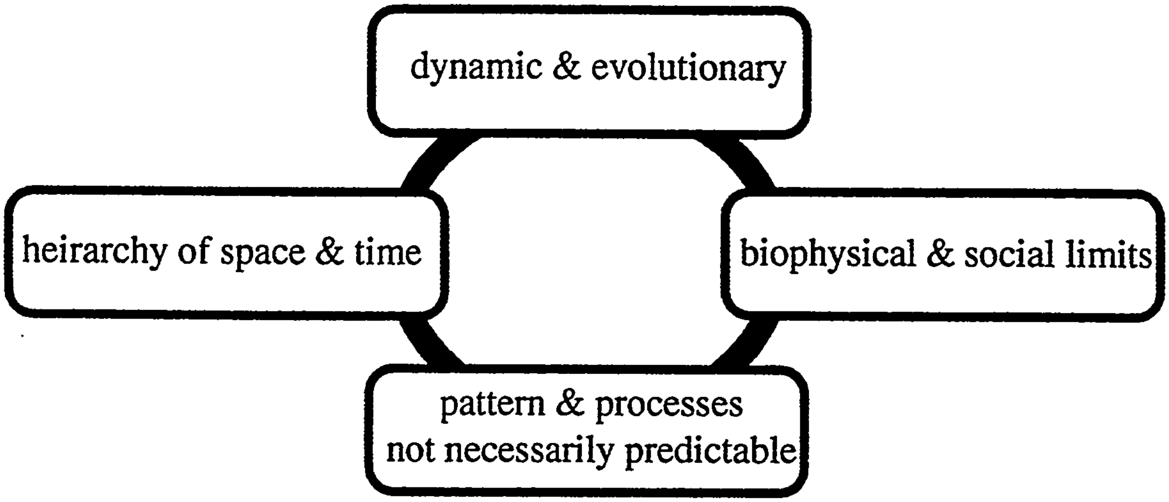


Figure 3. Typical model showing the attributes of Ecosystem Management (based on Science Integration Team 1994).

Examples are in the Greater Yellowstone Ecosystem, the Pacific Northwest Forests, and the Colorado Plateau.

For a substantial portion of the Colorado Plateau, the BLM, in association with many other agencies and organizations, has begun to merge individual planning initiatives into a regional perspective. This is shown conceptually in Figure 5.

Mention should be made of two key points regarding the concept illustrated. One, the existing plans are in various stages of adequacy and completeness to meet current management requirements; and these will be updated to a common standard. Two, the ecological overlay will provide a regional dimension to characterize ecosystem resource patterns in sufficient detail to improve individual planning decisions, establish ecological monitoring parameters, and focus management to the long-term health of the land. This ecological overlay will provide a new vision for spatial (regional) and temporal (long-term) objectives.

Work is just beginning to determine what this overlay will really look like. Obviously it will characterize some aspects of the basic landscape parameters of geologic setting, soil, vegetation, watershed, animals, visual quality, and health in functional ecosystem relationships. It must reflect questions of extinction (via the Endangered Species Act), biodiversity (especially in riparian settings as well as other key locations), and sustainability. Such an endeavor must draw information from the past, the present, and the future. Preparation of the overlay must begin with the end in mind, or at least with a reasonable view to the future. Understanding the effects of climate changes in this region can be significant in preparation of the ecological overlay, especially in relation to trends and long-term sustainability.

With the regional overlay, it will be important to determine and monitor key parameters within an ecological "band" or range of

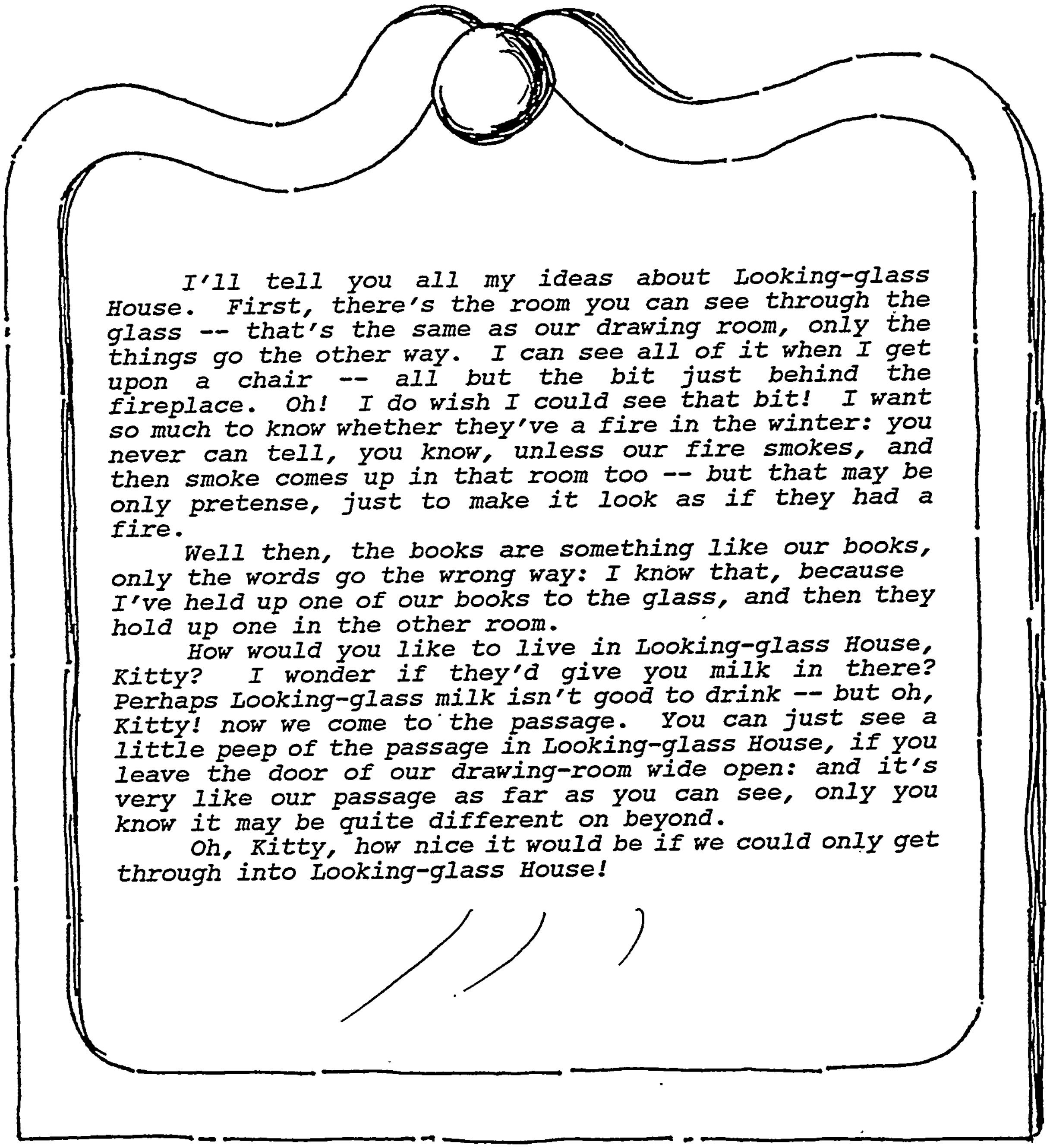


Figure 4. Through a Mirror, Darkly—Peering into the Past and into the Future takes curiosity, imagination, and perception. We must desire to see just a bit beyond, further into the passage (text from Carroll 1872).

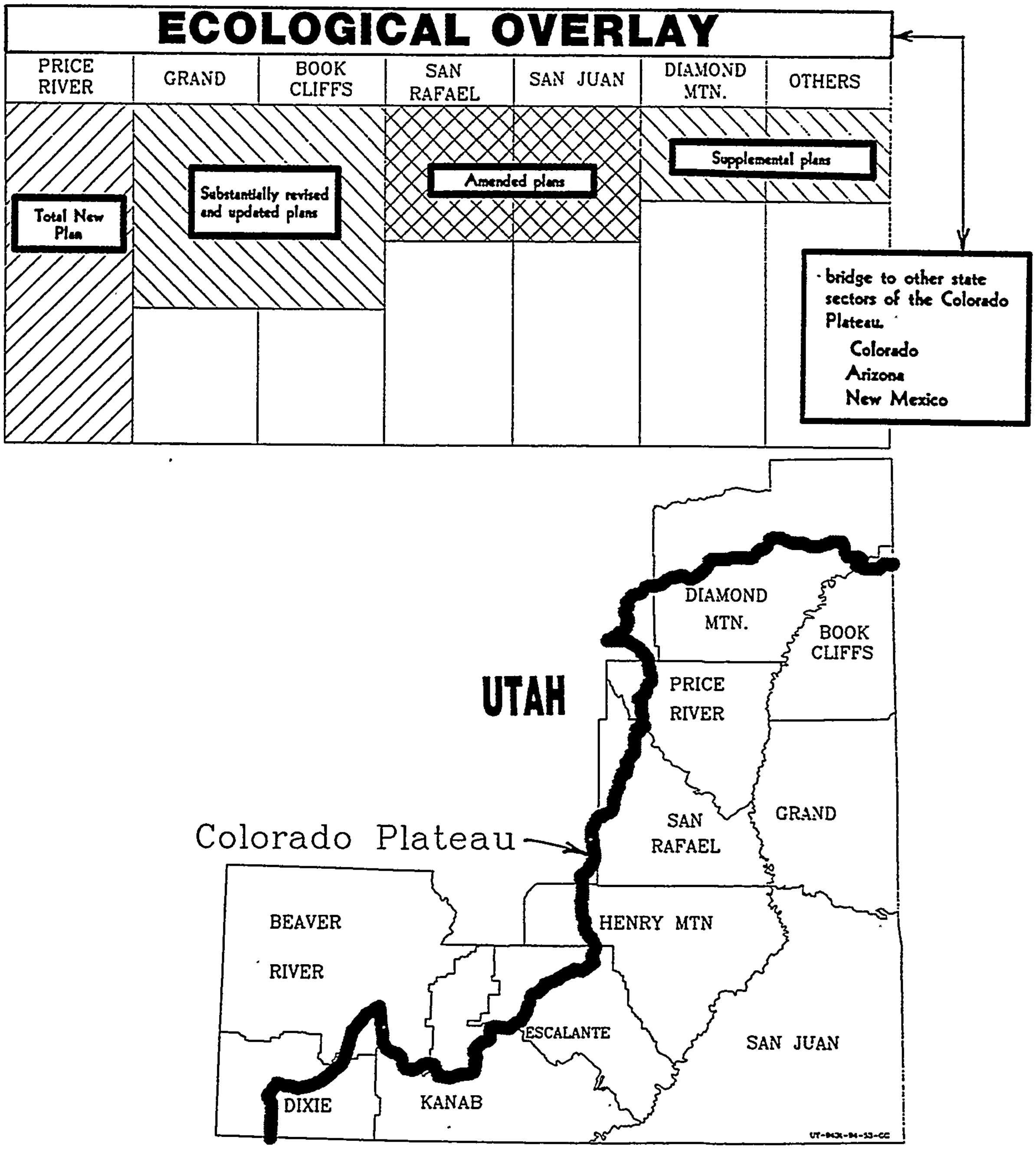


Figure 5. Conceptual diagram of the BLM Eastern Utah Ecosystem Planning Initiative. Resource management within the individual administrative units will become part of the larger vision for the Colorado Plateau.

variability. Indicators of environmental change, scientific findings, and ongoing data collection will be necessary for adaptive management. Such an adaptive approach will eventually allow managers to adjust away from a singular (normal) condition or target to reflect better annual and long-term climatic variations and other ecosystem variables, to be more proactive rather than reactive to natural patterns and related events. And (at least in theory) it then may be possible to reflect better the extended long-term regional climatic trends, such as the World Resources Institute prediction of warming by up to 4.5 degrees Centigrade by the year 2030 (Mintzer 1988). Thirty-five years is truly not very far ahead.

Attention to ecosystem management created renewed interest in the use of comparative photography, at least to record visually changing conditions over the past 100 years or so. While comparing old photos to current pictures may not be thought of as a new or a high-tech approach, it has been done with fascinating observations for several places in the West. Examples of comparative (or repeat) photo studies exist in Oregon, South Dakota, Montana, Nevada, Wyoming, Utah, Arizona, and other locations (Gruell 1983; Johnson 1986; Stephens and Shoemaker 1987; Rogers 1982; Rogers et al. 1984).

Utah BLM has begun to assemble old Colorado Plateau photos and replicate them (Hindley 1994). The photo comparisons often elicit "wow" as an audience response and then prompt questions as to why such changes occurred. Answers usually are speculative at this time, as the approach is interpretive and qualitative rather than quantitative; but it is compelling. For the most part, comparative photo studies indicate that vegetative densities have greatly increased since the early 1900s.

The photo sets shown in Figures 6 through 9 illustrate this documentation technique.

One of the more profound concepts associated with use of climate change information in resource planning and management is reflected in the famous phrase from *The Tempest*: "What's Past is Prologue" (Shakespeare 1609). Or as stated in *Four Quartets*:

> "Time present and time past
> Are both present in time future,
> And time future contained in time past"
> (T.S. Eliot 1943)

There are lessons to be learned—

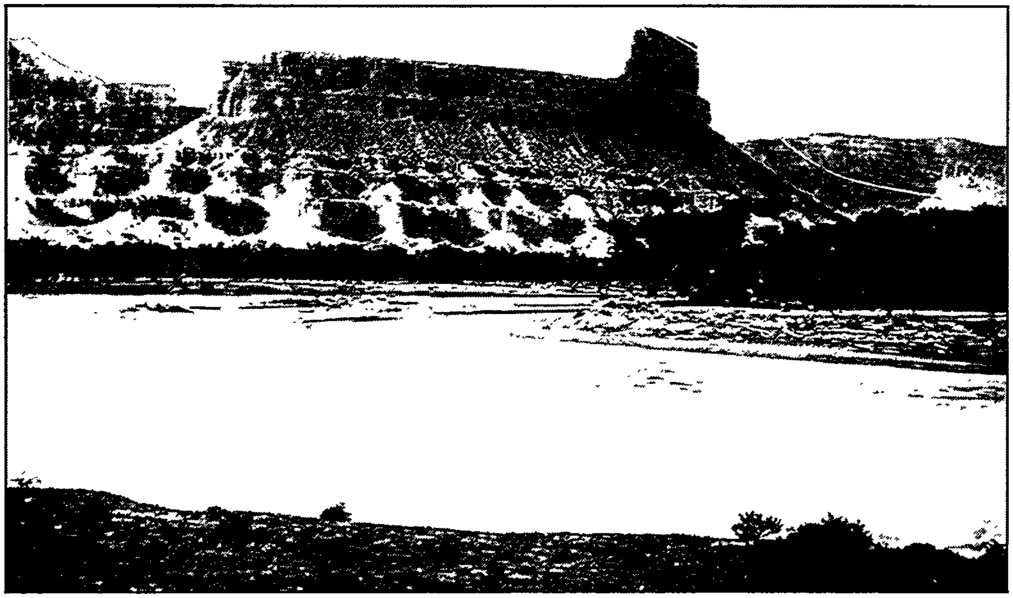
- Concerning change.
- Recognizing limits.
- Acknowledging man/nature relationships of previous cultures/civilizations.
- Factoring short-term, long-term, and very long-term timelines.
- Being aware of the relative scales of various human-caused and naturally occurring events.
- Adjusting human actions to natural patterns for improved harmonious environmental relationships.

THE CHALLENGES OF OUR TIME

In conclusion, and considering all of the foregoing in a rather holistic way, four major observations are noted regarding the full and effective use of climate change information for land management.

One, there is significant need for more knowledge of climate effects in ecological relationships and specific time-based trends. It is important to look at a variety of sources to piece together information pertaining to the past and the future. See Figure 10.

Two, there is need to increase the ability (individually, scientifically, and fiscally) to obtain such information and to apply it within the resource-managing agencies.



William Henry Jackson Photograph No. 1265, U.S. Geological Survey Photographic Library, Denver, Colorado

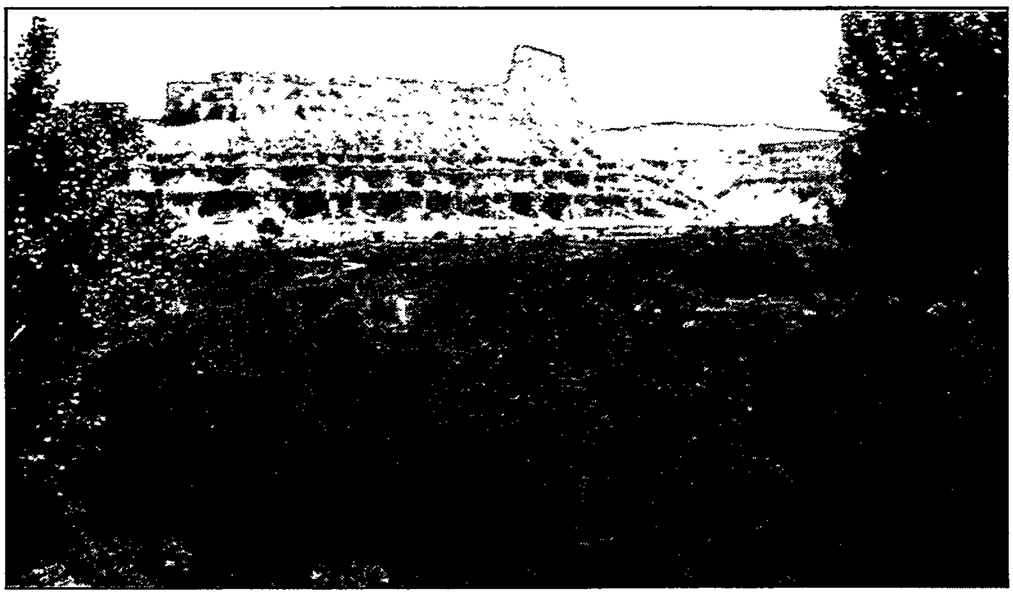
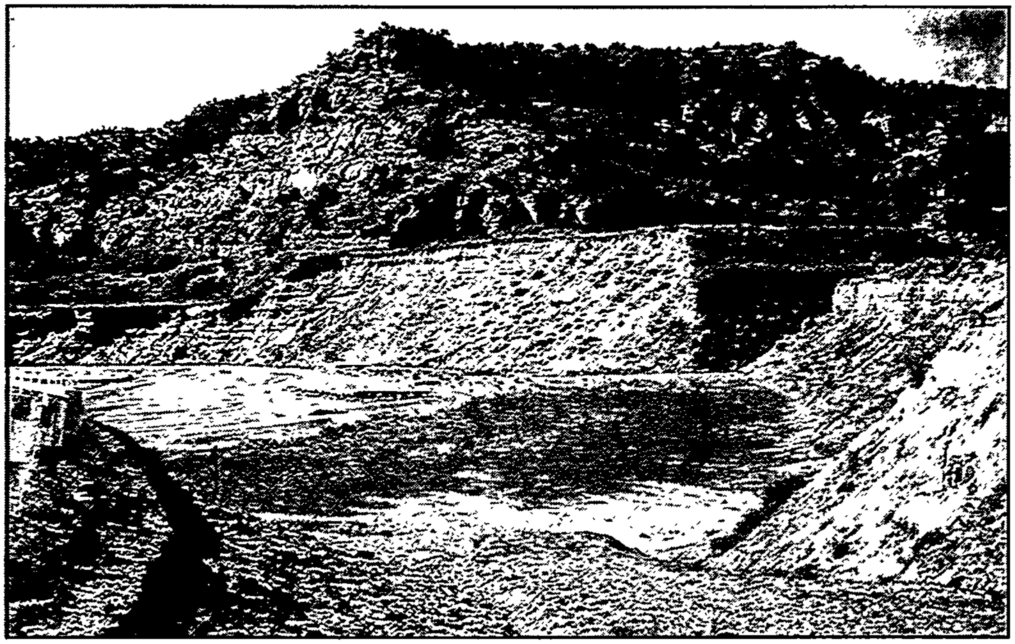
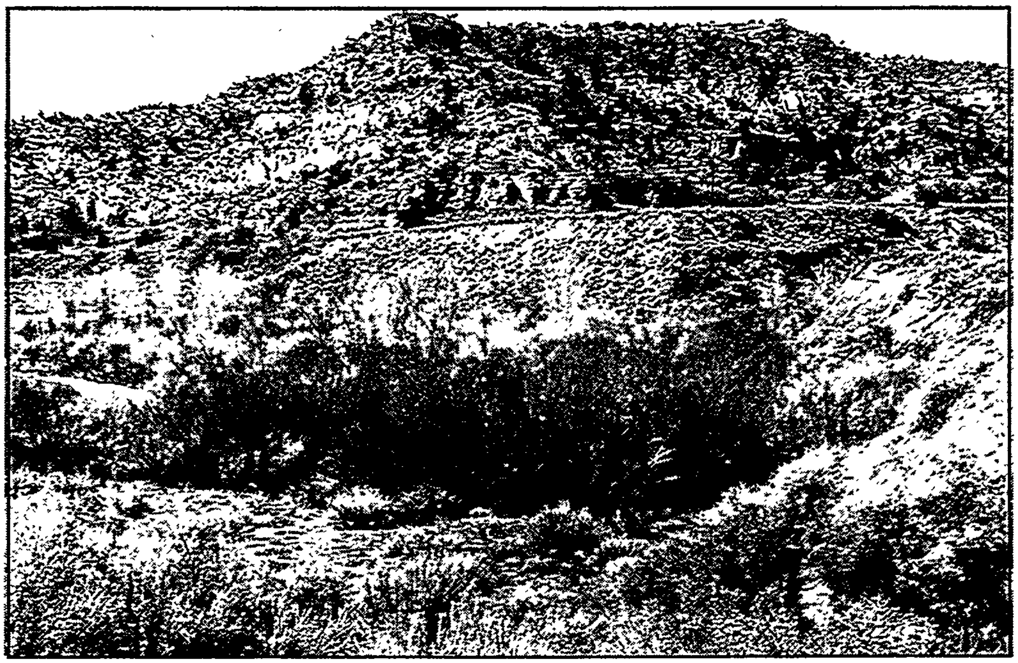


Photo Provided by U.S. Bureau of Land Management, Utah State Office, Salt Lake City, Utah

Figure 6. Gunnison Butte and the Green River. The top photo was taken by William H. Jackson, circa 1875. The repeat photo in 1993 demonstrates the loss of cottonwood galleries with a corresponding increase of streamside vegetation such as willow, rush species, cattail, and reed grass. There is some cottonwood reproduction due to spring events this low on the Green River. The upper terraces are occupied with tamarisk, a non-native species. Note the loss of the spire on the extreme left of the butte during the intervening 118 years between photographs. (Hindley 1994)

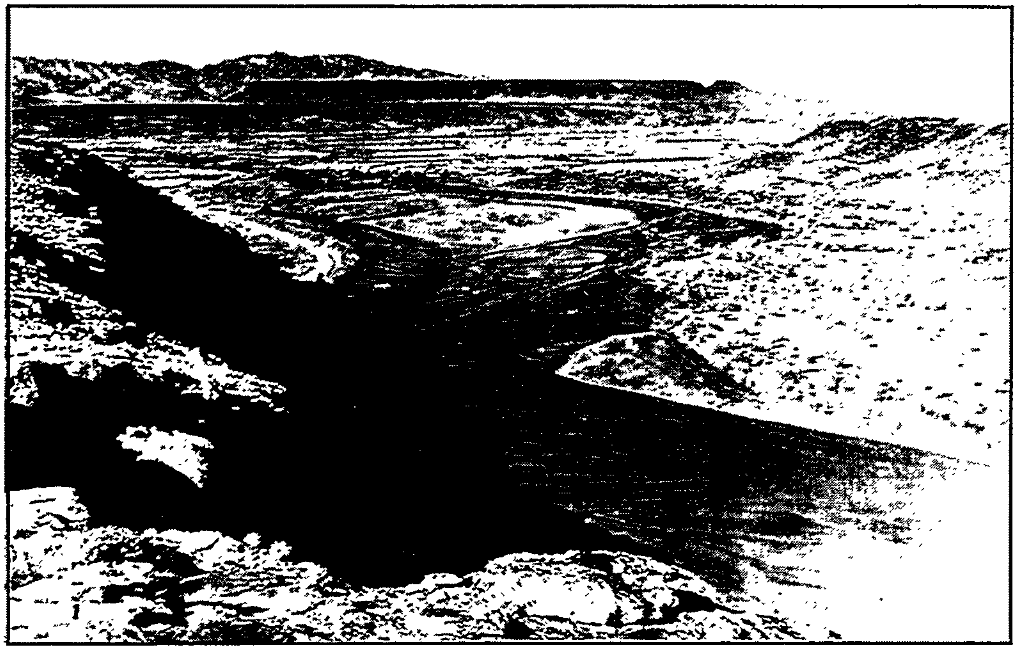


H.E. Gregory Photograph No. 950, U.S. Geological Survey Photographic Library, Denver, Colorado

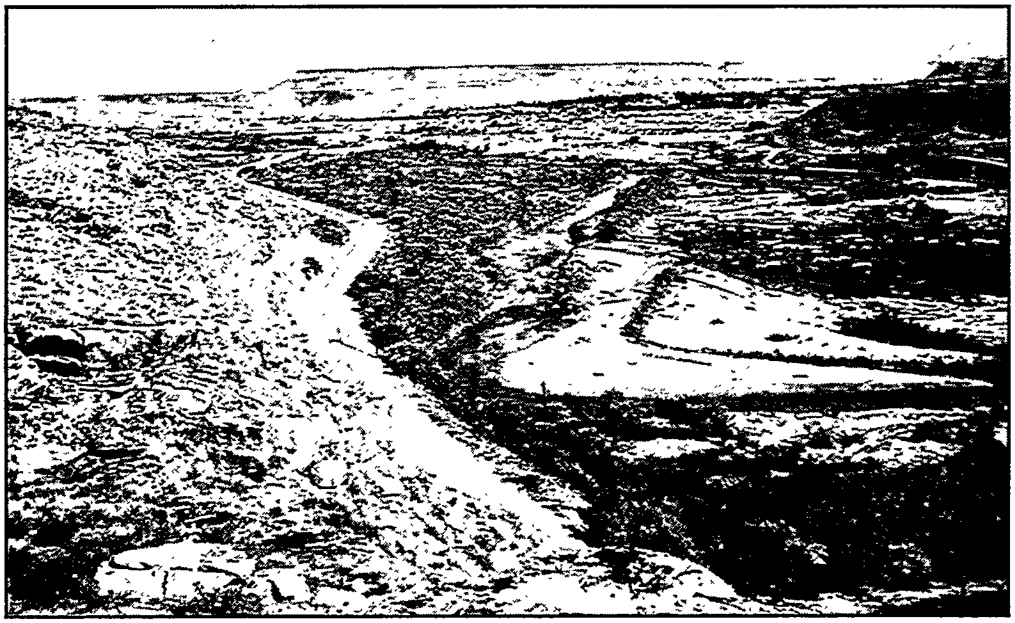


Photograph Provided by U.S. Bureau of Land Management, Utah State Office, Salt Lake City, Utah

Figure 7. Kanab Creek. The top photograph was taken in 1939. The lower photograph taken in 1993 illustrates vegetative stabilization on the steep-cut bank, and a marked improvement in the stream channel from a wide, shallow, braided system to a more narrow single stem channel with a well-defined floodplain. The active channel is now well-armored with sedge, rush, willow, cattail, and cottonwood species. Tamarisk (non-native) occupies the second terrace. (Hindley 1994)

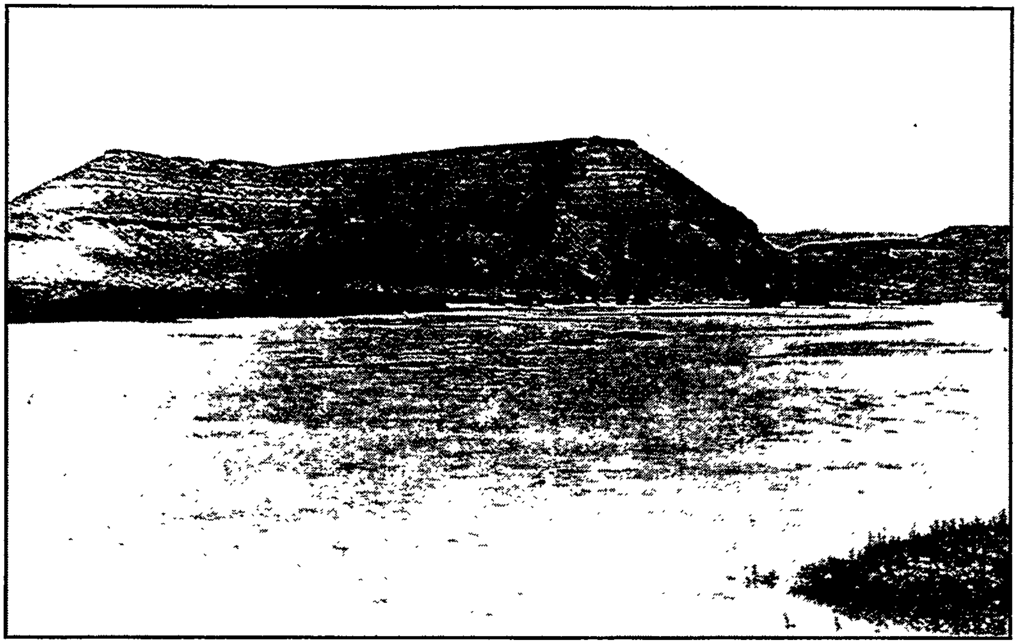


Utah State Historical Society Photograph No. 551.47 P.3., Salt Lake City, Utah



Photograph Provided by U.S. Bureau of Land Management, Utah State Office, Salt Lake City, Utah

Figure 8. Virgin River. The top photograph was taken in 1920 and the bottom photograph in 1993. The river is no longer braided with scoured and barren sand bars. Current increases in riparian vegetative (willow, rush, cattail, reed grass, and young cottonwood) growth provide habitat and other ecosystem values. The active channel is much more narrow, and defined with three distinct terraces. The upper two terraces are occupied with tamarisk, a non-native species. (Hindley 1994)



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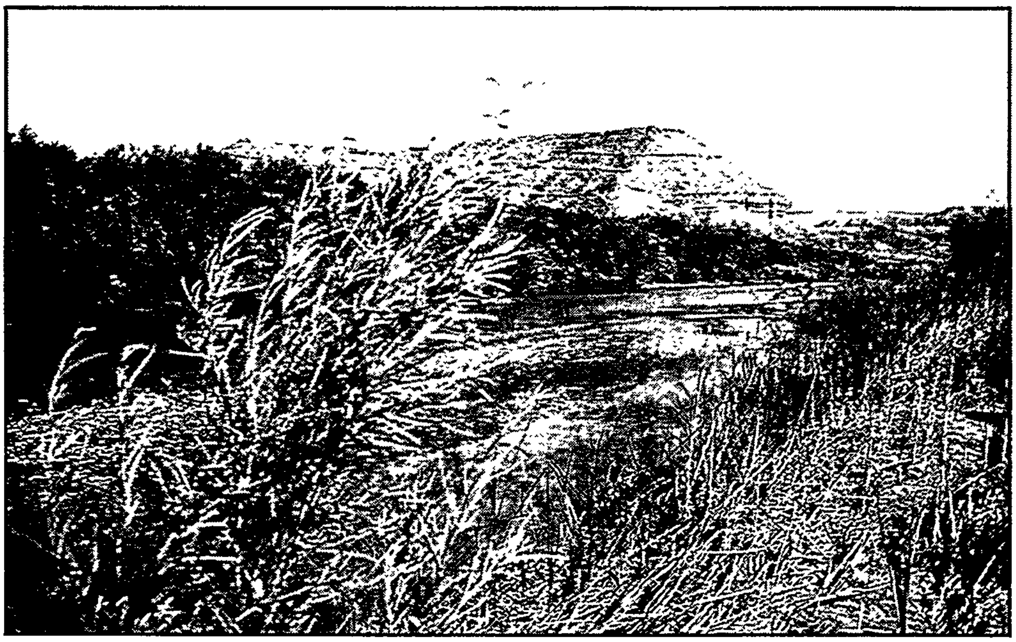

Photograph Provided by U.S. Bureau of Land Management, Utah State Office, Salt Lake City, Utah

Figure 9. Virgin River. The top photograph was taken in 1902, and the repeat photograph is dated 1993. Major changes include several feet of aggradation on the floodplain with the formation of a distinct channel and three major terraces. The lower terrace is now occupied with willows and tamarisk, a non-native species. (Hindley 1994)

SOURCES OF INFORMATION ON HISTORIC CHANNEL CHANGE OF KANAB CREEK

TYPE OF INFORMATION	RECORD LENGTH (years)	SOURCE	INFORMATION CONTENT AND RELIABILITY
Historic and scientific papers	210	Spanish explorers (1776); Mormon church records, Powell Survey diaries, Davis (1903), Mead (1903), Bryan (1925), Bailey (1935), Woolley (1946), Butler and Marsell (1972)	Poor to Excellent
General Land Office Surveys	113	Bailey and Burrell (1877)	Good to Excellent
Ground photographs	118	J.K. Hillers, 1871-1872; W. Bell, 1872; R.B. Stanton, 1890; H.J. Huether 1914; R.W. Bailey, A.R. Croft, & R.J. Becraft, U.S.F.S. 1930's; H.E. Gregory, U.S.G.S., 1930's	Excellent
Aerial photographs	50	Soil Conservation Service, 1939; U.S.G.S. 1953, 1957, 1976, 1983	Excellent
Gaging records	20	Kanab, Utah	Good
	15	Fredonia, Arizona	Good
Precipitation records	41	Kanab, Utah	Excellent
	61	Alton, Utah	Excellent
	85	Paria River basin (Graf and others, in press)	Excellent
	85	Regional analysis (Hereford, 1989; Hereford & Webb unpublished)	Excellent
Tree-ring records	~500	between Alton and Kanab (McCord, 1990)	Good
Alluvial stratigraphy	~5,300	upstream of Kanab (Smith, 1990)	Fair
Paleoflood record	~500	Kanab Canyon (Smith, 1990)	Poor

Figure 10. Information Sleuthing—This listing is a good example of the use of multiple data sources. Also, note length of record plus information content and reliability are reflected. (Adapted from Webb et al. 1991)

Three, there is need for greater (more harmonious) social vision to foster collaborative public acceptance of long-term, beneficial, management actions.

Four, there is need to accept that good land management must monitor and flow with the key aspects of natural change, focused on the health of the land and sustainable life-support systems. This requires a reborn awareness that change in nature will occur regardless of the human urge to suppress it or control it.

Now, to end this paper on a literary bit: While written about a location north of the Colorado Plateau, these words generally apply and provide a true long-term prospective:

> As Death Canyon Creek flows, it carries small, even microscopic, pieces of the mountains to be deposited in Phelps Lake. Slowly the mountains wear down and the lakes fill up. The natural world is dynamic, not static; it is always changing. As soon as a mountain range rises, forces of erosion begin to wear it down. As soon as

a valley drops, deposition begins to fill it. Humans measure these changes against their short lifespans and say "These mountains will last forever." It is difficult to understand the big changes that happen very slowly and on a geologic time scale. But you can see a delta forming slowly, ever so slowly, where Death Canyon Creek meets the still waters of Phelps Lake. Forever is just a matter of time. (Olsen and Bywater 1991)

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PALEOCLIMATIC DATA APPLICATION: LONG-TERM PERFORMANCE OF URANIUM MILL TAILINGS REPOSITORIES

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Keywords: *uranium mill tailings, long-term performance, climate change, paleoecology, engineered covers*

ABSTRACT

Abandoned uranium mill tailings sites in the Four Corners region are a lasting legacy of the Cold War. The U.S. Department of Energy (DOE) is designing landfill repositories that will isolate hazardous constituents of tailings from biological intrusion, erosion, and the underlying aquifer for up to 1,000 years. With evidence of relatively rapid past climate change, and model predictions of global climatic variation exceeding the historical record, DOE recognizes a need to incorporate possible ranges of future climatic and ecological change in the repository design process. In the Four Corners region, the center of uranium mining and milling activities in the United States, proxy paleoclimatic records may be useful not only as a window on the past, but also as analogs of possible local responses to future global change. We reconstructed past climate change using available proxy data from tree rings, packrat middens, lake sediment pollen, and archaeological records. Interpretation of proxy paleoclimatic records was based on present-day relationships between plant distribution, precipitation, and temperature along a generalized elevational gradient for the region. For the Monticello, Utah, uranium mill tailings site, this first approximation yielded mean annual temperature and precipitation ranges of 2 to 10 °C, and 38 to 80 cm, respectively, corresponding to late glacial and Altithermal periods. These data are considered to be reasonable ranges of future climatic conditions that can be input to evaluations of groundwater recharge, radon-gas escape, erosion, frost penetration, and biointrusion in engineered earthen barriers designed to isolate tailings.

INTRODUCTION

From 1942 through the 1960s, the processing of uranium ore for the U.S. Army's Manhattan Engineer District and later for the U.S. Atomic Energy Commission produced more than 20 million metric tons of low-level radioactive and sometimes chemically toxic

[1]Work performed for the U.S. Department of Energy Grand Junction Projects Office under DOE contract number DE-AC04-94AL96907.

tailings (Portillo 1992). The U.S. Government used uranium for nuclear weapons production and nuclear power generation. Many of the uranium mills operated in western Colorado, northwestern New Mexico, northeastern Arizona, and eastern Utah, a mostly arid and semiarid area known as the Four Corners region. Today, in accordance with Title I of Public Law 95-604, the Uranium Mill Tailings Radiation Control Act (UMTRCA), the U.S. Department Energy (DOE) is cleaning up tailings at abandoned uranium millsites to reduce human health and environmental risks. The strategy for isolating hazardous materials involves covering tailings piles with engineered layers of soil and rock.

Over time, even in the desert ecosystems of the Four Corners region, hazardous constituents of buried uranium mill tailings may be subject to transport. DOE has been mandated to design disposal facilities that will isolate tailings for at least 200 years and, to the extent achievable, for 1,000 years (EPA 1983). Considering this unprecedented longevity requirement, design approaches must be devised that exceed standard engineering practices. Conventional disposal facilities have a finite design life (EPA 1989). In contrast, tailings repositories should be designed to persist without maintenance for hundreds of years. Effects of long-term changes in waste-site environments, and particularly possible changes in climate, need to be addressed early in the repository design process. Release of hazardous materials from buried tailings and the performance of engineered repositories designed to isolate tailings are greatly influenced by climate.

We begin this paper with a synopsis of contaminant transport pathways and the performance of tailings repository designs. We show that contaminant transport is most dependent on the amount and movement of water in engineered repository covers and that soil water content and movement are climate driven. In subsequent sections, we propose a paradigm for assessing the long-term performance of engineered covers and present the case for using natural analogs in concert with conventional modeling and physical testing methods. We propose paleoclimate change as a natural analog of the limits of possible future climate change at tailings disposal sites. Last, we present a reasonable range of future climate scenarios for the Monticello uranium mill tailings repository in southeastern Utah that is based on a simplified reconstruction of late Quaternary paleoclimate records from the Four Corners region.

CONTAMINANT TRANSPORT AND THE PERFORMANCE OF ENGINEERED COVERS

Several uranium mill tailings sites in the Four Corners region have been or will be remediated by placing tailings in near-surface repositories (Portillo 1992; DOE 1995). Radioactive and hazardous constituents of tailings buried in these landfill repositories may be vulnerable to transport via water infiltration, gaseous release, soil erosion, frost penetration, and intrusion by plant roots and burrowing animals. Engineered covers or barriers designed to isolate contaminants from these transport pathways consist primarily of layers of soil and rock (DOE 1989). Two general types of covers have been designed or constructed at disposal sites in the Four Corners region (Caldwell 1992): rock-armored, low-permeability covers (Figure 1) and vegetated soil covers with capillary moisture barriers (Figure 2). The low-permeability designs rely on compacted fine-soil layers to slow radon escape and deep infiltration of rainwater. The surface layer of rock provides erosion protection, and a sand bedding layer underlying the rock is intended to divert rainwater laterally. The vegetated soil cover design consists of a topsoil layer over a sand and gravel layer. The topsoil layer has favorable physical properties for storing rainwater close enough to the surface to be removed by evapotranspiration (Gee et al. 1992). The capillary barrier increases the water storage capacity of the topsoil layer.

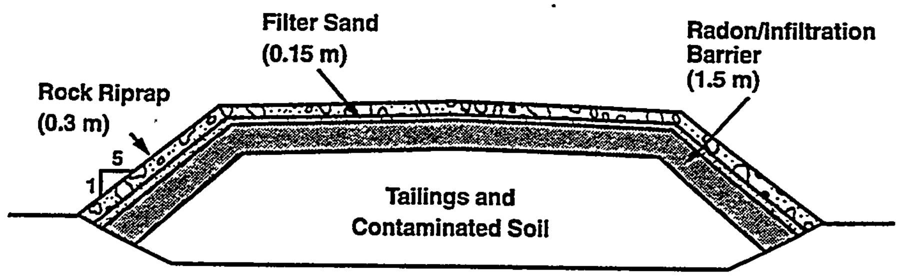

Figure 1. Typical rock-armored, low-permeability cover for uranium mill tailings repositories (after DOE 1989).

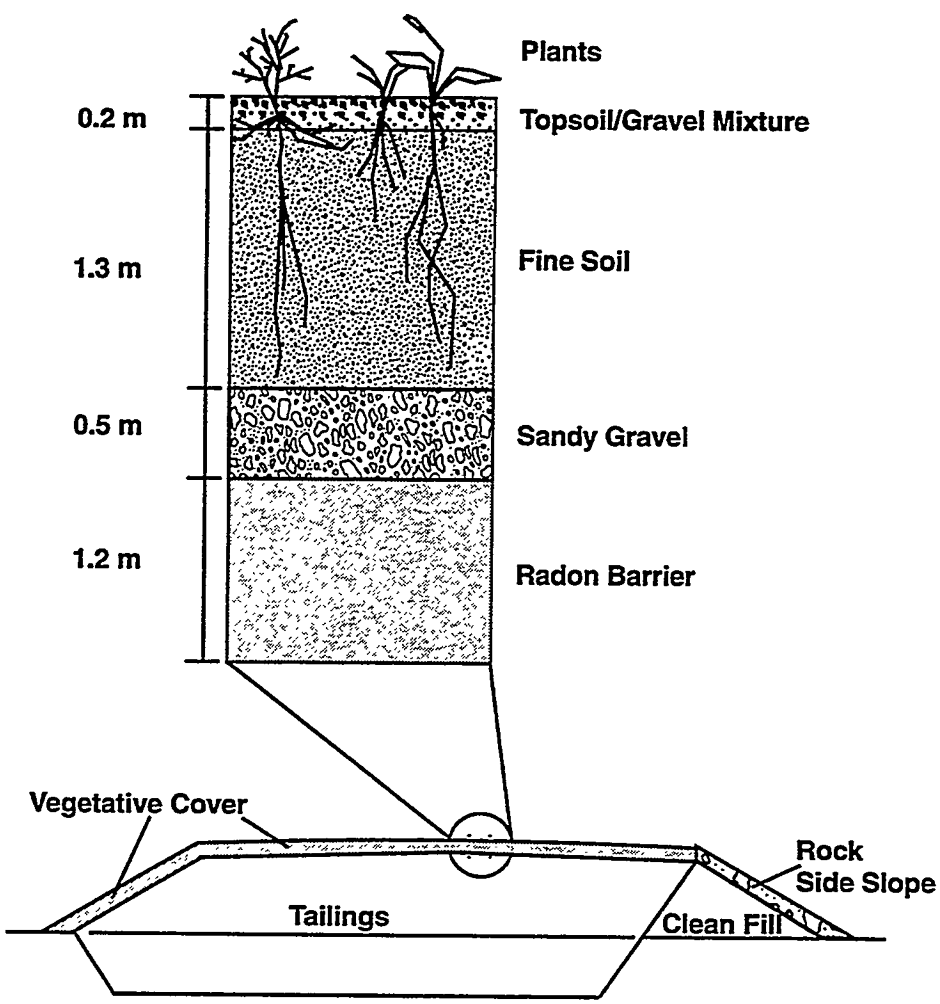

Figure 2. Typical vegetated soil cover with a capillary moisture barrier.

With vegetation present, gravel mixed into the soil surface controls top-slope erosion, similar to a desert pavement, without influencing the soil water balance of the system (Waugh et al. 1994b).

This section is a review of (1) contaminant transport and release pathways in uranium mill tailings repositories and (2) the performance of engineered covers designed as barriers to those pathways.

Water Infiltration

Rainwater and snowmelt not lost by runoff enters the soil overlying the tailings and becomes distributed within the soil profile in response to water potential gradients. The soil water could conceivably evaporate from the soil surface, be extracted by plants and returned to the atmosphere as transpiration, remain stored in the soil, or drain through underlying tailings potentially mobilizing and carrying contaminants to the water table. Engineered covers typically consist of compacted soil layers with a mandated laboratory permeability of 1 x 10^{-7} cm s^{-1} or less and overlying sand and gravel layers to divert water laterally (DOE 1989; EPA 1989).

Capillary barriers (Figure 2) have been proposed as an alternative to compacted soil layers at some arid and semiarid waste disposal sites (Waugh et al. 1983; Nyhan et al. 1990; Wing and Gee 1993). Capillary barriers consist of a fine-textured soil "sponge" overlying a layer of coarse sand and gravel. In accordance with the Richards phenomenon (Richards 1950), the capillary barrier impedes unsaturated flow because high tensions in the small pores of the fine-textured soil prevent movement of water into the larger pores of the coarse-textured layer. Water will enter the coarse-textured layer when accumulations just above the textural break approach saturation and pore pressures approach zero (Hillel 1980). Water extraction by plants rooted in the fine soil can prevent water accumulation above the textural break (Waugh et al. 1991; Gee et al. 1992; Anderson et al. 1993). Lysimeter studies have shown that, with vegetation present, a capillary barrier consisting of 150 cm of silt loam overlying sand and gravel layers will prevent drainage even with an annual precipitation of greater than 480 mm (Wing and Gee 1993). The storage capacity of a soil placed over a capillary barrier may be as much as twice the storage capacity, or field capacity, of the same soil without a capillary barrier (Campbell et al. 1990).

Gaseous Release

Engineered covers also function to limit releases of harmful gases. Covers on uranium mill tailings piles are designed to limit the average surface flux of radon-222 to less than 20 pCi m^{-2} s^{-1} (EPA 1983). For most designs, the highly compacted fine-textured soil layer designed as a water infiltration barrier also serves to slow radon diffusion (DOE 1989). The performance of this layer as a radon barrier is dependent on the physical, hydrological, and radiological properties of each distinct tailings and soil layer. Numerical models suggest that the release of radon is most sensitive to soil moisture content in the radon barrier, followed by the radium-226 concentration, radon-emanating fraction, and radon diffusion coefficient (Smith et al. 1985).

Because an excessive thickness of native soil may be required to reduce radon flux to permissible levels, thin layers of sodium-amended bentonite and asphalt have been investigated as alternatives. Both have been proposed as combined water infiltration and gas diffusion barriers (DOE 1989; Wing and Gee 1993). Laboratory hydraulic conductivities of 1 x 10^{-9} cm s^{-1} have been achieved with commercially manufactured bentonite mats (Daniel and Estornell 1990). Attributes of asphalt include low radon flux (less than 2 pCi m^{-2} s^{-1}), low hydraulic conductivity (less than 10^{-9} cm s^{-1}), and high ductility (1,300 percent elongation) (Freeman and Gee 1989; Gee et al. 1989).

Erosion

Soil loss caused by overland flow, channel erosion, and wind deflation could expose and disperse buried waste under extreme conditions or, more likely, reduce the thickness of the cover, leading to contaminant transport by other pathways (e.g., water infiltration). Overland flow on waste-disposal sites involves the detachment of soil particles from the cover by raindrop splash and transport in free-flowing surface water, sometimes concentrating in rills and gullies (Walters and Skaggs 1986). Wind transports soil particles by surface creep, saltation, and resuspension. Wind erosion can be particularly rapid leeward of topographic highs (Ligotke 1993).

The primary erosion control issue is if vegetation alone will adequately limit soil loss or are gravel mulches, gravel admixtures, or rock riprap necessary to armor arid and semiarid sites where vegetation is sparse and less dependable (Beedlow 1984). Live vegetation and organic litter disperse raindrop energy, slow flow velocity, bind soil particles, filter sediment from runoff, increase infiltration, and reduce surface wind velocity (Wischmeier and Smith 1978). Armoring soil covers with rock or a thick gravel mulch to disperse raindrop energy and reduce flow velocity (Figure 1) is a common practice in arid environments with sparse vegetation (DOE 1989; Caldwell 1992). Procedures that are based on tractive sheer stress calculations have been developed that provide considerable design conservatism (NRC 1990).

Thick rock or gravel armor, however, can compromise infiltration barriers by reducing evaporation (Groenevelt et al. 1989; Kemper et al. 1994), possibly causing deep drainage (Gee et al. 1992), and by creating habitat for deep-rooted plants (DOE 1992). As an alternative to rock riprap and gravel mulches, erosion studies (Finely et al. 1985; Ligotke 1993; Gilmore and Walters 1994) and soil water balance studies (Waugh et al. 1991; Waugh et al. 1994b; Sackschewsky et al. 1995) favor the use of a combination of vegetation and gravel admixtures (Figure 2). These studies suggest that moderate amounts of gravel can be mixed into the cover topsoil to reduce both water and wind erosion with little effect on plant habitat or soil water balance.

Frost Penetration

As temperatures drop and soil layers in engineered covers freeze, water drawn toward the freezing front causes desiccation cracking (Chamberlain and Gow 1979), formation of ice lenses, and frost heaving, particularly in compacted clay layers (Suter et al. 1993). Desiccation and frost cracking may lead to increased permeability and gas diffusion in engineered cover layers within the frost zone (Caldwell 1992). Frost heaving may cause engineered layers to become mixed, thereby destroying the integrity of layer interfaces (Bjournstad and Teel 1993). Various methods have been used to estimate and compare local frost penetration depths for diverse combinations of soil type, vegetation abundance, and snow cover (DOE 1988; Suter et al. 1993). Frost penetration calculations are used to estimate the thickness of random fill layers needed to ensure that low-permeability barriers and gas-diffusion barriers are placed below a calculated extreme frost depth.

Root Intrusion

Although plants typically are desirable on engineered covers for soil water extraction and erosion protection (see above), unwanted vegetation can counteract these benefits. Deep-rooted plants inhabiting engineered covers may root through soil covers deep into underlying waste, actively translocating and disseminating contaminants in aboveground tissues (Klepper et al. 1979; Klepper et al. 1985; Arthur 1982; Morris and Fraley 1989; Driver 1994). Root intrusion also indirectly influences waste isolation. Macropores left by decomposing plant roots act as channels for water and gases to rapidly bypass the soil mass in low-permeability barriers (Hillel 1980; Morris and Fraley 1989; Passioura 1991). Roots may clog coarse-textured lateral drainage layers (DOE 1992), potentially increasing rates of infiltration through underlying compacted soil layers. Plant roots also tend to concentrate in and extract water from buried clay layers, causing desiccation and cracking. This can occur even when overlying soils are nearly saturated (Hakonson 1986), indicating that the rate of water extraction by plants can exceed the rehydration rate of the buried clay. Furthermore, roots within the waste zone may alter soil chemistry, mobilizing contaminants (Cataldo et al. 1987; Driver 1994).

Cover designs often include either physical or chemical barriers to plant root intrusion. Physical barriers consist of soil textural boundaries and highly compacted soil layers. Buried clay layers may reduce rooting depths (Foxx et al. 1984), but at arid sites, root densities may actually be higher in buried clay layers because of greater water retention. As mentioned above, desiccation may render clay barriers ineffective (Hakonson 1986; Reynolds 1990). By retaining soil water close to the surface, thus creating a habitat for shallow-rooted species, capillary moisture barriers also function as root intrusion barriers (Cline et al. 1980; Hakonson 1986).

Some cover designs include highly compacted soil layers as root intrusion barriers (Suter et al. 1993; Wing and Gee 1993). Agronomists have long recognized that highly compacted soils cause stubby and gnarled root growth (Passioura 1991). However, there is considerable variation among plant species in their ability to penetrate compacted soils (Materechera et al. 1991). The mechanisms by which compacted soils impede root elongation are unclear. Physical mechanisms, root elongation controlled by pore size and a soil penetration resistance that exceeds root cell turgor pressure (Greacen and Oh 1972), and biochemical mechanisms, hormonal control of root sensitivity to pore pressure (Kays et al. 1974), may both be important (Bengough and Mullins 1990).

Time-release herbicides offer a short-term alternative to physical root barriers. A system developed by Pacific Northwest Laboratory consists of extruded polymer pellets impregnated with the herbicide trifluralin and bonded to a polypropylene geotextile (Burton et al. 1986). Trifluralin vapor released at a controlled rate a few centimeters into the soil prevents root cell division without killing plants. It effectively deflects roots just above the geotextile surface while allowing plants to continue growing, extracting water, and stabilizing the soil.

Animal Intrusion

Burrowing animals can transport buried waste either directly, by vertical displacement to the surface of a soil profile, or indirectly, by altering physical and hydraulic properties that control soil erosion and water balance (Hakonson et al. 1992; Suter et al. 1993). Vertical displacement of contaminated materials by burrowing animals can result during excavation of burrows, through ingestion, and as external contamination on skin and fur (O'Farrell and Gilbert 1975; Klepper et al. 1979; Winsor and Whicker 1980; Hakonson et al. 1982; McKenzie et al. 1982; Arthur and Markham 1983). Once in the surface environment, contaminants may be transferred through higher trophic levels and carried off site (O'Farrell and Gilbert 1975; Arthur and Markham 1983). Burrowing can also increase soil erosion. Loose soil cast to the surface by burrowing animals is vulnerable to wind and water erosion (Winsor and Whicker 1980; Hakonson et al. 1982; Cadwell et al. 1989). Burrowing influences soil water balance by decreasing runoff, increasing rates of water infiltration and vapor diffusion, and increasing evaporation because of greater surface area for drying and natural drafts (Cadwell et al. 1989; Sejkora 1989).

Gravel and cobble (or riprap) layers in multilayered cover designs (Figure 2) are cited as a physical deterrent to burrowing animals (Cline et al. 1980; Hakonson 1986; Caldwell 1992; Wing and Gee 1993). Burrowing mammals are deterred by loosely aggregated gravels or relatively massive rock. Furthermore, multilayered earthen designs often include a soil water-retention layer with a thickness that exceeds the depths that most rodents burrow. Little is known, however, about the activity of invertebrates in multilayered earthen cover designs. We do not know the effectiveness of these designs as barriers to harvester ants that may tunnel 3 m deep into arid waste-burial sites.

PERFORMANCE ASSESSMENT USING NATURAL ANALOGS

Performance Assessment Paradigm

Our performance assessment approach combines modeling, physical tests, and characterization of natural analogs (Figure 3). All three components require climatic data (Petersen et al. 1993). Models of soil-water movement (Fayer et al. 1992), erosion (Lane and

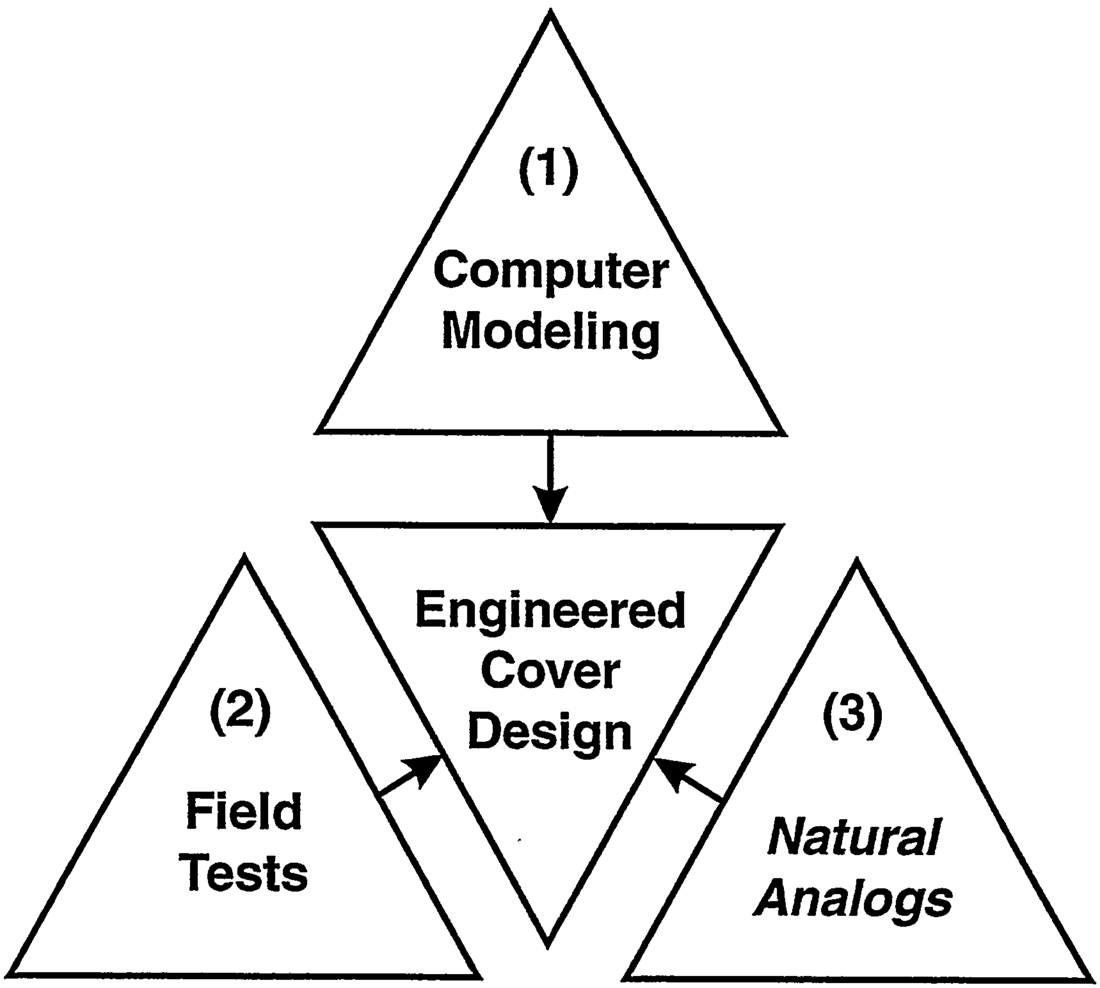

Figure 3. Generalized performance assessment paradigm for uranium mill tailings repository covers.

Nearing 1989), and radon diffusion (NRC 1984) engender an understanding of the complexity of environmental processes acting on engineered covers and can numerically simulate responses of designs to myriad conditions. Field and laboratory tests, although expensive, provide the only real measures of performance and are needed to confirm model predictions (Gee et al. 1992; Waugh et al. 1991). Modeling and field test results have shown that water infiltration of the cover, recharge, radon diffusion, biointrusion, and disposal cell stability are all sensitive to long-term changes in precipitation, temperature, and water extraction by plants.

The greatest uncertainties in designing covers for tailings repositories stem from the scientifically challenging need to extrapolate the results of short-term tests to the long performance periods required by regulatory agencies. Standard engineering approaches that are based on laboratory tests, short-term field demonstrations, and numerical predictions implicitly assume that initial conditions of material properties and of processes that drive contaminant transport will persist indefinitely. In contrast, engineered covers must be viewed as evolving components of larger, dynamic ecosystems. We must recognize that, over time, the performance of engineered covers will change in response to many of the same processes that drive contaminant transport.

Natural analog studies (Figure 3) provide clues from past environments as to possible long-term changes in engineered covers (Waugh et al. 1994a). Analog studies involve the use of logical analogy to investigate natural and archaeological occurrences of materials, conditions, or processes that are similar to those known or predicted to occur in some part of the engineered cover system. As such, analogs can be thought of as uncontrolled, long-term experiments. Natural analog studies are needed in the performance assessment process to understand and evaluate emergent properties in the evolution of engineered covers that do not arise during short-term tests or from numerical predictions extrapolated from the results of short-term tests.

Natural analog studies play a dual role in this process; at first, qualitative, and later, more quantitative. During early design phases, natural analogs can be used to identify environmental processes that will act on the cover over time providing a rational basis for developing conceptual designs. Later, quantitative data from natural analog studies can be used to define scenarios for possible modes of failure, to devise treatments for controlled laboratory and field tests, and as input values for performance assessment models. Finally, natural analogs may have a role in communicating the results of the performance assessment to the public. Evidence from natural systems may help demonstrate that numerical predictions have real-world complements. Long-term performance issues that could be addressed using analogs include ecological change, pedogenesis (soil development), and climate change (Figure 4).

Why Use Paleoclimate Analogs?

Current cover design approaches rely on meteorological records for evaluations of long-term performance (DOE 1989). Meteorological data can and should be used to model and test cover performance for present climatic conditions, but not for possible future changes in climate. Climatologists generally agree that during the next decades and centuries, global climatic variation will exceed the historical record. This has occurred naturally in the past (Houghton et al. 1990; Crowley and North 1991) and may recur as the lower atmosphere warms in response to increasing concentrations of anthropogenic carbon dioxide and other greenhouse gases (Hansen et al. 1988; Ramanathan 1988).

Paleoclimate records provide not only a window on the past but also on possible local manifestations of future global change. By comparison, models of global and regional climate may enhance our understanding of climate-change drivers but are inadequate for

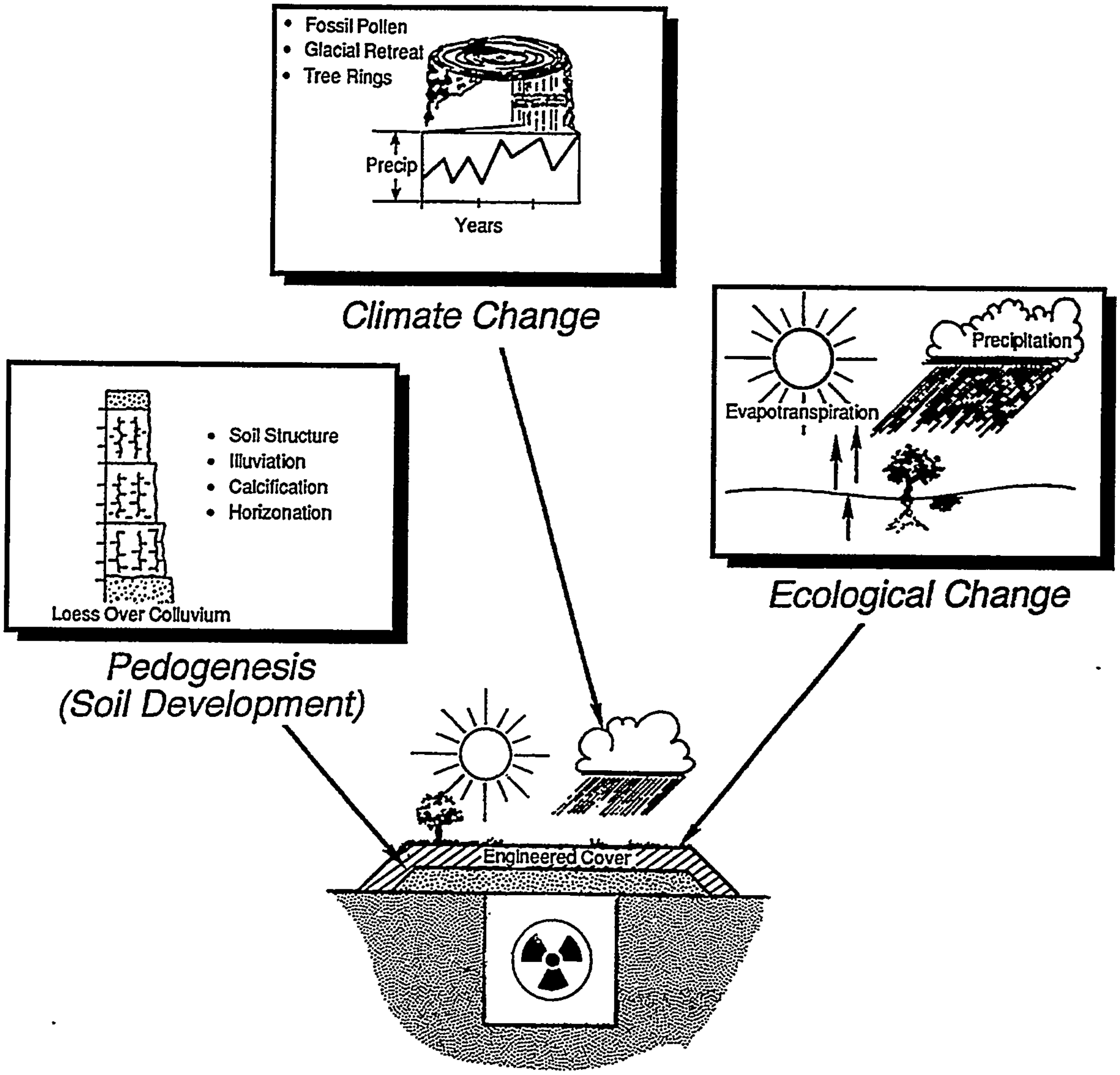

Figure 4. Issues concerning the long-term performance of engineered covers that can be addressed by studying natural analogs.

local climate projections. Nested regional models are continually improving (Giorgi et al. 1993), but available global climate models that could address the 1,000-year design life of tailings repositories are incapable of resolution on the spatial scales required (Hansen et al. 1988; Mitchell 1989; Houghton et al. 1990). Ranges of possible future climate at tailings disposal sites in the Four Corners region can best be inferred from natural proxy records of past climate change. A reasonable range of climatic conditions 1,000 years into the future can be captured within a period spanning the Holocene and Late Pleistocene. Proxy climate records covering this period have been developed for the Four Corners region from tree rings, plant and animal remains preserved in packrat middens, plant pollen buried in fluvial sediments, and Anasazi archaeology.

RECONSTRUCTING FOUR CORNERS PALEOCLIMATES

This first approximation of local paleoclimates of Four Corners tailings sites relies on proxy climate records, an understanding of current climate drivers, present-day relationships between plant distribution and climate, and assumptions of cyclical climate and consistent responses of vegetation to climate change.

Climate Drivers

Winter (November to March) precipitation enters the region with migrating low-pressure systems following the westerly jet stream. Troughs of low pressure typically follow a route north of a West Coast high-pressure ridge, entering the United States in the Pacific Northwest and tracking southward along the eastern side of the Rocky Mountains, often bringing only partly cloudy skies and strong southwest winds to the Four Corners. An anomalous westward displacement of the winter high-pressure ridge routes the low-pressure trough south off of the West Coast, entering the United States as far south as central California and tracking through the Great Basin and Colorado Plateau to the northeast. Once established, this pattern tends to recur, producing a succession of wet winter storms (Changnon et al. 1993). The pattern may be associated with El Nino-Southern Oscillation (ENSO) events (Redmond and Koch 1991), during which low mid-latitude storms draw moisture from the subtropical jet stream and bring heavy precipitation to the southwest (Cayan and Peterson 1989). Tree-ring records suggest that ENSO events have fueled anomalously wet southwestern winters for at least the past 300 years (Swetnam and Betancourt 1990).

Warm, relatively dry air masses governed by high-elevation anticyclones centered over the Mexican Highlands dominate the April, May, and June climate of the Four Corners region. In early July, a monsoon-like low pressure usually develops over the Colorado Plateau, drawing warm, moist air from the Gulf of Mexico and Gulf of California and spawning convective storms as a result of surface heating, convergence, or orographic lifting (Bryson and Lowery 1955; Hales 1974; Tang and Reiter 1984). Development of a low-pressure trough in the Salton Sea region of southern California enhances airflow from the Gulf of California (Reyes and Cadet 1988). The summer convective storms of the Four Corners region form in clusters many tens of kilometers across and, on average, persist for less than an hour (Barry and Chorley 1970).

Interplay of Climate and Vegetation

The reconstruction of Four Corners paleoclimates assumes that (1) precipitation and temperature have an overriding influence on the elevational distribution of plants and, therefore, (2) past shifts in the elevational distribution of plants reflect past shifts in the elevational distribution of temperature and precipitation. In fact, plant distributions are delimited by many interacting factors that not only vary over time and space but also exhibit concomitant and synergistic effects. Elevational shifts occur when the complex of environmental conditions above or below a species' distribution changes such that conditions become within its physiological tolerances. Environmental conditions may include a favorable change in temperature or effective moisture, but also may be influenced by changes in species interactions that can diminish, augment, or otherwise offset climate-induced shifts. Further, considering the physiographic discontinuities in environmental gradients and the seasonality aspect of climate change, the elevational interplay of climate and vegetation should not be considered constant.

Recognizing this complexity and interdependence of factors that limit plant distribution, and the naiveté of thinking that the importance of single factors can be isolated, for the purposes of this study we proceed with the above assumptions. After all, the Holocoenotic concept of causal factors holds that factors are interactive, not that they have equal weight (Billings 1952, 1978).

Figure 5 depicts a present-day elevational distribution of vegetation, temperature, and precipitation in the Four Corners region. Again, assuming some consistency of vegetation and climate interactions, evidence of past changes in the distribution of plants preserved at sites scattered along the elevational gradient is the basis for reconstructing past climates. Temperature and precipitation curves were derived from meteorological data compiled by Petersen et al. (1987) for 12 sites located between 1,300 and 2,700 m elevation in southwestern Colorado and southeastern Utah. The generalized plant species distribution curves are based on numerous sources (Arno and Hamerly 1984; Betancourt et al. 1990; Maher 1961; Petersen 1988). Lower limits of plants are generally considered to be set by moisture deficiencies and upper limits by low temperatures. Figure 6 is a map of paleosite and tailings site locations. Table 1 presents the types of proxy data, dates, and references for the paleoclimate sites used in this study.

MONTICELLO TAILINGS DISPOSAL SITE CLIMATE

Records of Past Climate Change

The records in Table 1 indicate that plant distribution in the Four Corners region shifted hundreds of meters in elevation since the Late Pleistocene in response to fluctuations from arid to subhumid climates (Figure 7). Records from 18,000 B.P. to the present are well-constrained by radiocarbon dates and span the transition from the last, full glacial maximum to the present interglacial period. These paleorecords reflect long-term shifts in average temperature and precipitation and not the high variability that exists in meteorological records (Nielson 1986).

Records of past climate change in the Four Corners region provide working limits for ranges of temperature and precipitation at tailings disposal sites. For example, the modern vegetation at Monticello, Utah, (Figure 6) is scrub oak with pinyon-juniper on southern exposures and ponderosa pine on northern exposures (Figure 5). Present mean annual temperature and precipitation are 8 °C and 38 cm, respectively (Figure 5). During the Late Pleistocene, subalpine forests dominated vast areas now occupied by pinyon-juniper woodlands (Figure 7). This predominance of cold-tolerant species, downward expansion of subalpine trees, and apparent absence of warm-season species reflect a much wetter, colder climate than today (Lao and Benson 1988; Thompson 1990). The Laurentide ice sheet, thrusted up into the lower atmosphere, may have split the jet stream into two branches with the southern branch forced south across northern California, Nevada, Utah, and Colorado (COHMAP Members 1988), resulting in long wet winters, cool summers, and an essentially nonexistent summer monsoon in the Four Corners. On the basis of a synthesis of Late Pleistocene paleorecords, we have set working-level values of mean annual temperature at 2 °C and precipitation at 80 cm for Monticello.

Paleoclimate data from Table 1 sources record a post-glaciation climate (13,000 to 10,500 B.P.) that continued wetter but warmer, with upper plant limits moving upslope but little change in lower plant limits (Figure 7). Conditions of global warming increased the moisture-holding capacity of Pacific air masses; however, the jet stream continued tracking south of slowly retreating continental ice (Ruddiman and Wright 1987), sustaining wet winters in the Great Basin and Colorado Plateau. By the early Holocene (approximately 10,000 B.P.), the Four Corners climate was significantly warmer and drier than previously, although seasonal patterns of wet winters and dry summers persisted. A shift toward a more modern summer monsoonal climate was delayed until the ice sheet retreated into northeastern Canada.

The middle Holocene (8,000 to 4,000 B.P.) was warmer and wetter than today—approximately 10 °C and 60 cm precipitation at Monticello (Figure 7). The packrat midden

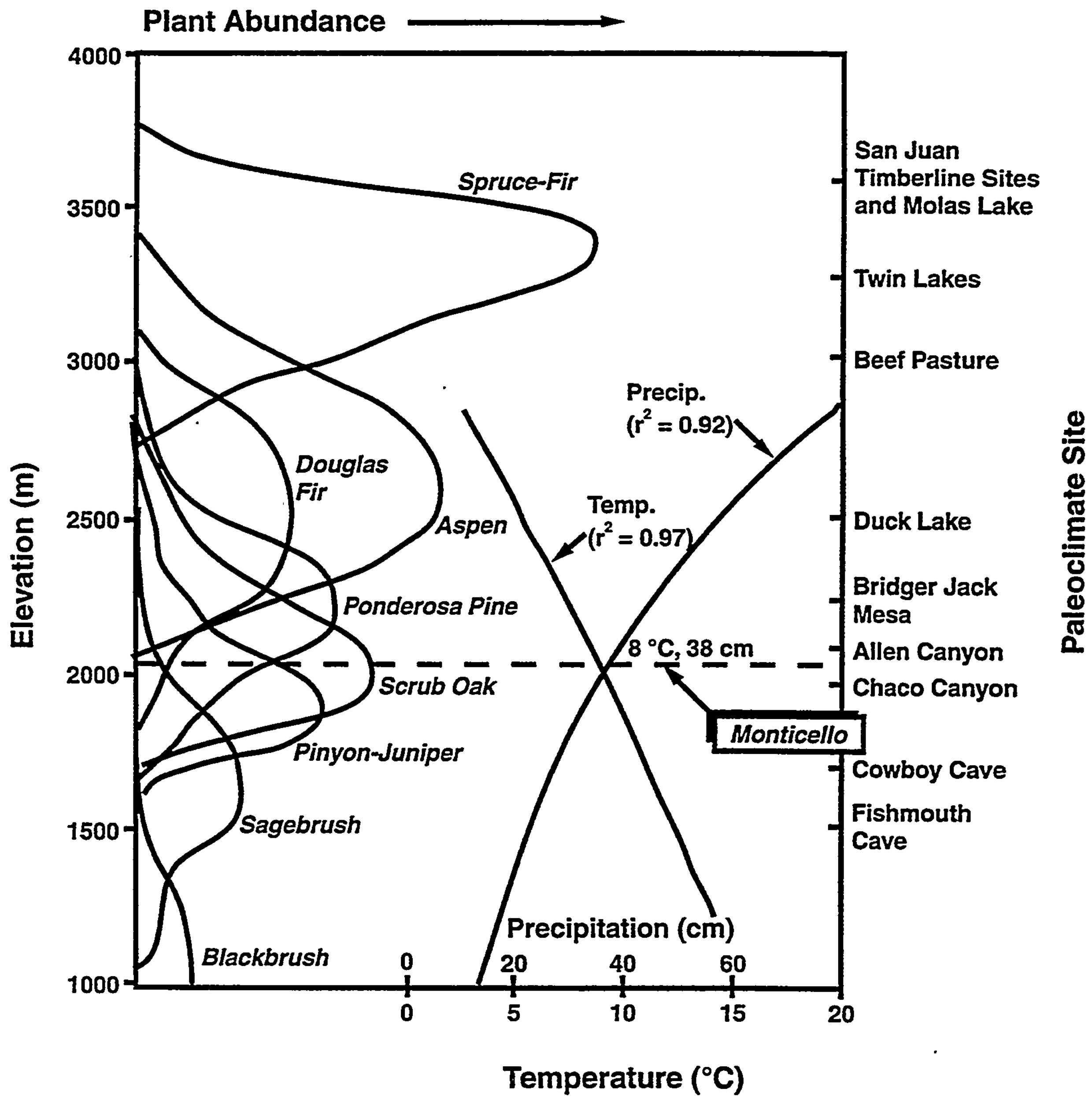

Figure 5. Elevational distribution of present-day vegetation, mean annual temperature, mean annual precipitation, and paleoclimate sites in the Four Corners region. The Monticello, Utah, tailings site is shown as an example.

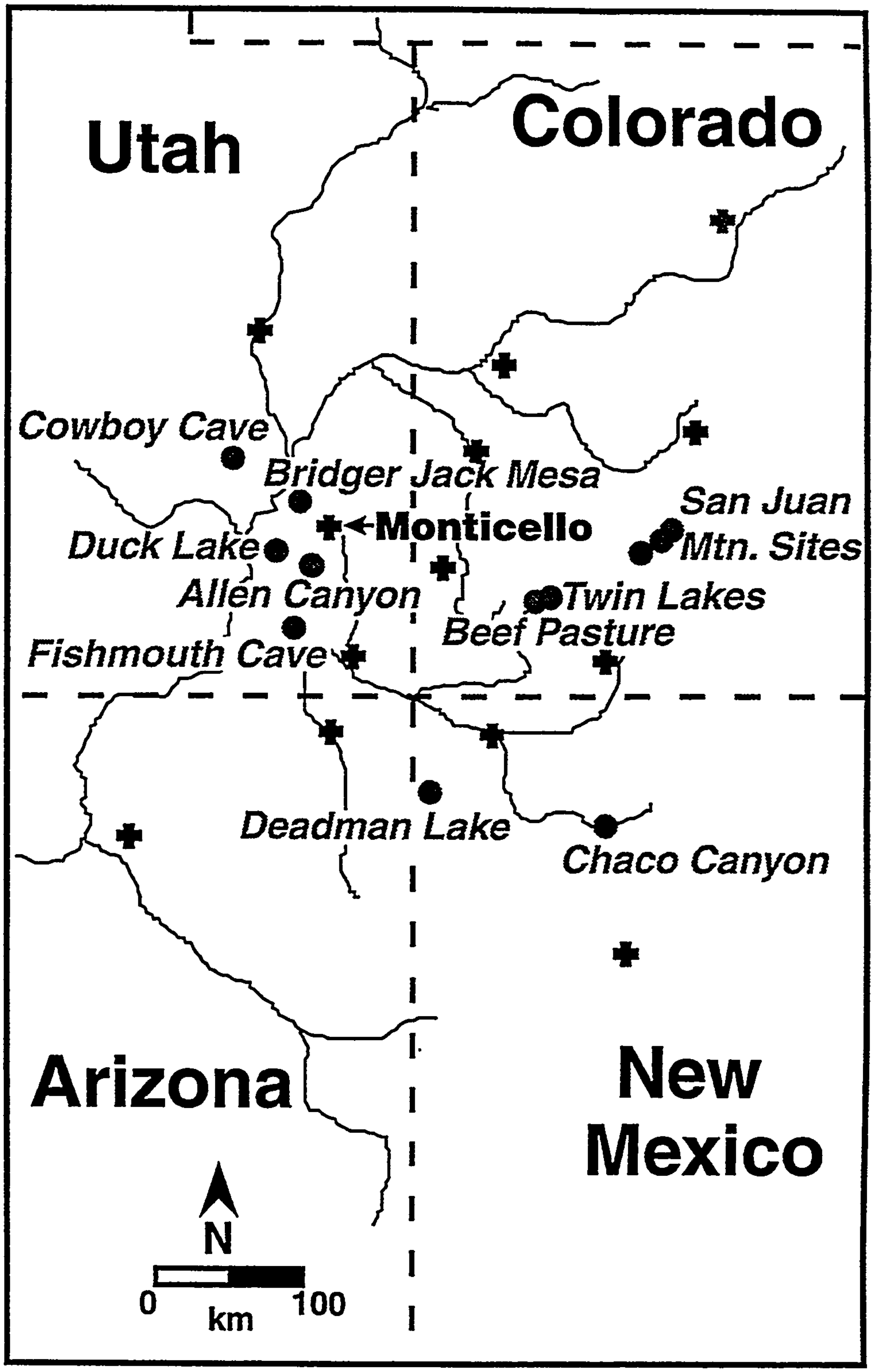

Figure 6. Map of paleoclimate sites (•) and uranium mill tailings sites (+) in the Four Corners region.

Table 1. Proxy data sources, dates, and references for paleoclimate sites used to reconstruct Four Corners region climates.

Paleoclimate Site	Proxy Data	Dates[a]	Reference
Fishmouth Cave	Packrat middens	13,800 B.P to present	Betancourt et al. 1990
Cowboy Cave	Packrat middens, pollen, and plant macrofossils	13,000 B.P. to present	Jennings 1980
Chaco Canyon	Packrat middens	10,600 B.P. to present	Betancourt et al. 1990
Allen Canyon Cave	Packrat middens	11,300 B.P. to present	Betancourt 1984
Duck Lake	Pollen	Late Pleistocene	Betancourt and Biggard 1985
Bridger Jack Mesa	*Pinus edulis* dendrochronology	500-yr record	Van Pelt 1978
Beef Pasture	Pollen	6,000 B.P. to present	Petersen 1988
Twin Lakes	Pollen	10,000 B.P. to present	Petersen 1988
Molas Lake, San Juan Mountains	Pollen	16,000 B.P. to present	Maher 1961
San Juan Mountains Timberline	Macrofossils and pollen in timberline bogs	10,000 B.P. to present	Carrara et al. 1991

[a]B.P. = before present.

record of vegetation change reflects cold and relatively dry winters, an increase in both summer and annual temperatures, a shift to monsoon-dominated summers, and greater effective moisture than at present (Betancourt 1984; Betancourt and Biggard 1985). Upper treeline was at least 80 m and as much as 140 m higher than at present (Carrara et al. 1991). This period, known as the Altithermal, has been viewed as an analog of future greenhouse warming, although the latter may develop more rapidly (within 50 to 100 years) and have warmer winters (Houghton et al. 1990). By about 3500 B.P., upper treeline had dropped to near its present elevation.

Petersen (1985, 1988) coupled pollen and archaeological records to infer fluctuations in the seasonality of climate in the Four Corners region for the last 2,000 years. Changes in pollen influx for pinyon pine, a middle Holocene newcomer to the Four Corners region, may reflect changes in the northern latitudinal position of the summer monsoon boundary. The northern limit of Anasazi

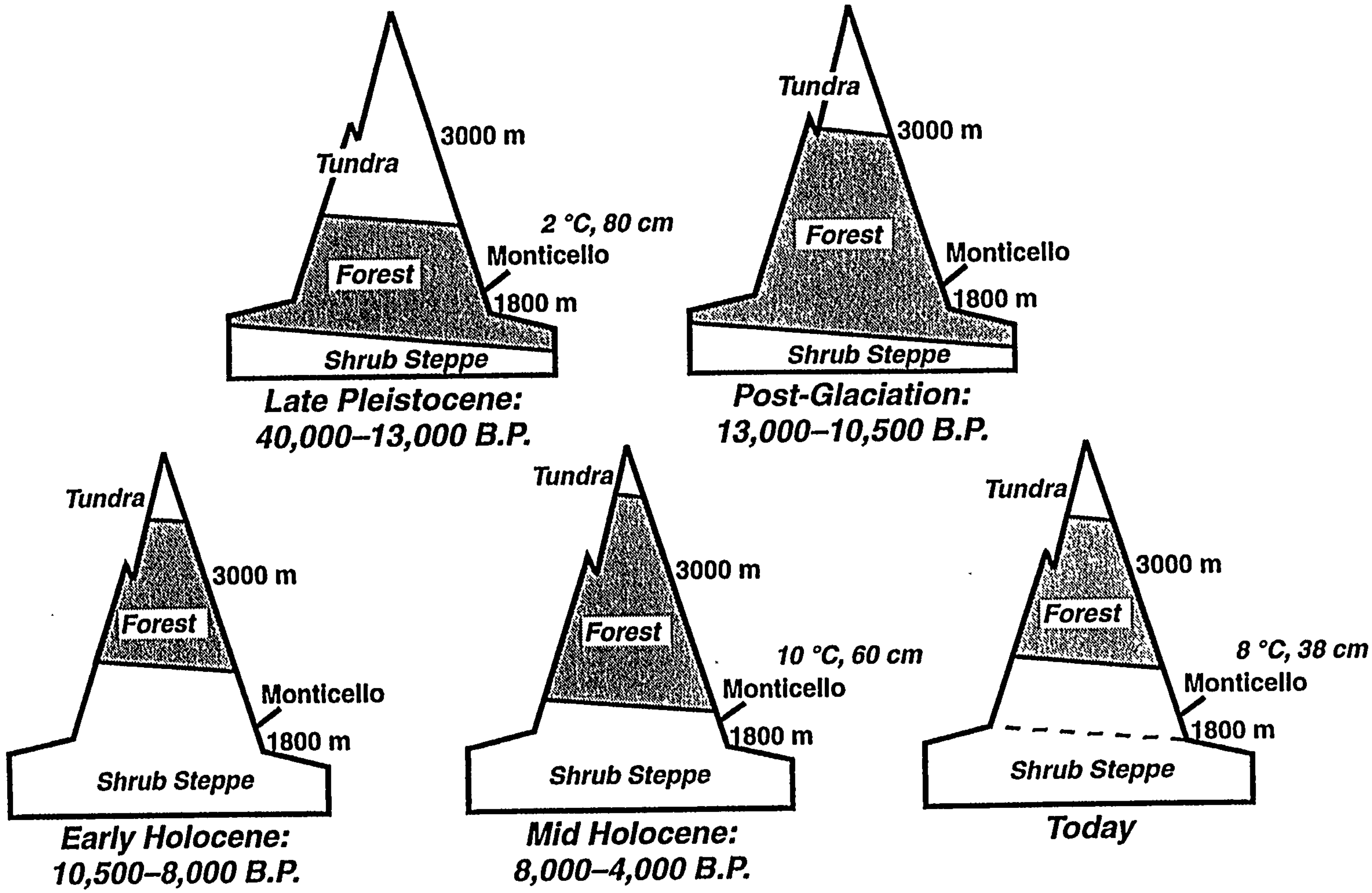

Figure 7. Generalized Late Pleistocene and Holocene shifts in forest boundaries in the Four Corners region. The present lower extent of pinyon pine, a Late Holocene newcomer, is marked with a dashed line.

occupation also appears to have fluctuated in response to the northern position of the monsoon boundary. For example, a high pinyon pollen influx between A.D. 700 and 1200 corresponds to a period of increasing Anasazi population in the region. Anasazi were subsistence farmers who relied on summer monsoon rains to raise corn and other crops.

Historical climate change continued to influence human activities. During the years 1250 to 1850, a period called the Little Ice Age, colder climate displaced European agriculture to the south. Summer rains abated, growing seasons shortened, and the frequency of forest fires increased in the Four Corners region. With the end of the Little Ice Age, around 1840, pinyon pine began encroaching in woodland parks with deeper soils (Van Pelt 1978), reflecting an increase in summer rainfall (Petersen 1988). Sustained by relatively high effective moisture, dry farming near Blanding in southeastern Utah began in 1905 but was abandoned in 1932 because of drought. Tree-ring records show that this was the wettest period in the Four Corners region during the last 300 years (Stockton 1976).

Future Climate Change

Global mean temperature may increase by 1.8 to 5.2 °C in the next century, in response to an industrial age buildup of carbon dioxide (CO_2), methane, and other gases (Houghton et al. 1992). Model projections of the magnitude of warming vary, depending on whether factors such as CO_2 fertilization, feedback from stratospheric ozone depletion, and the radiative effects of sulfate aerosols are taken into account. Model projections of precipitation responses to greenhouse warming also are inconsistent (Houghton et al. 1990; Crowley and North 1991; Washington and Meehl 1984; Wilson and Mitchell 1987; Schlesinger and Mitchell 1987). Some regions may be effectively wetter and others drier, depending on the balance of the greater potential evaporation and the greater water-holding capacity of a warmer atmosphere.

Greenhouse warming may eventually be overwhelmed as the earth plunges into another ice age. Models of cyclic astronomical forcing of climate agree that, without anthropogenic disturbances, a long-term cooling trend that started about 6,000 years ago will continue, climaxing with a major glaciation in about 60,000 years (Imbrie and Imbrie 1980; Berger et al. 1991). In contrast, aperiodicity in the timing of past ice ages is evident in oxygen isotope records (Winograd et al. 1992). Other paleorecords suggest that certain feedback mechanisms have caused rapid and unpredictable transitions into ice ages (Berger and Labeyrie 1987; Phillips et al. 1990).

Despite uncertainty about drivers of future climate change, climate extremes in the next 1,000 years likely will not exceed those associated with the last glacial and interglacial periods (Spaulding 1985). Therefore, paleorecords of full glacial and Altithermal climates in the Four Corners region provide reasonable ranges of possible future climate and should be incorporated in assessments of the long-term performance of tailings disposal facilities. For Monticello, Utah, full glacial and Altithermal climate reconstructions provide working levels of 2 to 10 °C mean annual temperature and 38 to 80 cm mean annual precipitation.

SUMMARY

The U.S. Department of Energy is working to comply with legislation requiring isolation of hazardous tailings constituents for up to 1,000 years. Although tailings disposal facilities must persist indefinitely, cleanup strategies that are based on conventional landfill designs fail to account for long-term changes in climate at disposal sites. Climate change during the design life of tailings repositories will likely exceed the meteorological record as the lower atmosphere warms in response to increasing concentrations of greenhouse gases. Groundwater recharge, radon-gas escape, erosion, frost penetration, biointrusion, and the engineered earthen barriers designed to isolate tailings from these pathways all will be greatly influenced by climate change.

Past climate change in the Four Corners region may provide reasonable ranges of possible future climate for use in modeling and field tests of the performance of tailings repositories. Late Pleistocene and Holocene climate change was inferred from proxy data sources, including tree rings, packrat middens, lake sediment pollen, and archaeological records. Climate reconstructions from these data relied on present-day relationships between plant distribution, precipitation, and temperature along a generalized elevational gradient for the region. Past precipitation and temperature records were then developed from the paleo-records of changes in plant communities preserved at sites scattered along the elevational gradient. For the Monticello, Utah, tailings repository, this approach yielded mean annual temperature and precipitation ranges of 2 to 10 °C, and 38 to 80 cm, respectively, corresponding to late glacial and Altithermal paleorecords.

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Appendix B

Tour Agenda

Agenda for Tour
September 14, 1994

Time	Schedule
7:30 a.m.	Leave Grand Junction, Colorado
9:00	Tour Stop 1: Green River, Utah, Uranium Mill Tailings Repository
9:30	Leave Green River
10:45	Tour Stop 2: Visitors Center and relic Douglas fir stand, Island In the Sky District, Canyonlands National Park
11:30	Leave Canyonlands National Park
12:00	Tour Stop 3: Arches National Park Visitors Center
12:20 p.m.	Leave Visitors Center (lunch provided, bring water)
12:40	Tour Stop 4: Arrive at Delicate Arch parking area, 2-mile round-trip hike to Bison Alcove packrat midden site, return to parking lot
4:30	Leave Arches National Park
4:45	Tour Stop 5: Overlook of Atlas uranium mill tailings restoration site
5:30	Dinner in Moab, Utah
7:00	Leave Moab
9:00	Arrive in Grand Junction, Colorado