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Constructing Seasonal Climograph Overlap Envelopes from Holocene Packrat Midden Contents, Dinosaur National Monument, Colorado

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Five *Neotoma* spp. (packrat) middens are analyzed from Sand Canyon Alcove, Dinosaur National Monument, Colorado. Plant remains in middens dated at approximately 9870, 9050, 8460, 3000, and 0 ^{14}C yr B.P. are used to estimate Holocene seasonal temperature and precipitation values based on modern plant tolerances published by Thompson *et al.* (1999a, 1999b). Early Holocene vegetation at the alcove shows a transition from a cool/mesic to a warmer, more xeric community between 9050 and 8460 ^{14}C yr B.P. *Picea pungens, Pinus flexilis*, and *Juniperus communis* exhibit an average minimum elevational displacement of 215 m. *Picea pungens* and *Pinus flexilis* are no longer found in the monument.

Estimates based on modern plant parameters (Thompson *et al.*, 1999a) suggest that average temperatures at 9870 ^{14}C yr B.P. may have been at least 1° to 3°C colder in January and no greater than 3° to 10°C colder in July than modern at this site. Precipitation during this time may have been at least 2 times modern in January and 2 to 3 times modern in July. Discrepancies in estimated temperature and precipitation tolerances between last occurrence and first occurrence taxa in the midden record suggest that midden assemblages may include persisting relict vegetation. © 2002 University of Washington.

Key Words: **packrat; midden; Holocene; vegetation change; climate change; climate envelope.**

INTRODUCTION

Packrat (*Neotoma*) middens often contain records of local vegetation change because packrats forage for food and nesting material and transport these items to their dens (see Betancourt *et al*., 1990). Middens and their contents, commonly cemented with crystallized packrat urine if the den is sheltered, can be preserved for tens of thousands of years and, thus, can preserve records of plant assemblages through time.

However, seasonal temperature and precipitation estimates from midden assemblages can be difficult to ascertain. Vegetational inertia or "lag" can occur following a climate shift and is influenced by dispersal rate, competition from those taxa persisting at the site after conditions suitable for their establishment have changed, or other environmental factors such as microclimate or soil structure suited to, or even generated by, existing taxa (Davis *et al*., 1986; Cole, 1985). Taxa can also persist in place without reproducing (Thompson, 1988) and, therefore, represent only an end member of their climate tolerance range in a midden assemblage. Thus, middens can contain taxa that may not wholly represent the climate that they are thought to characterize. Additionally, lack of data on the relations between climate and plant distributions has hampered paleoclimate reconstructions using taxa recovered from packrat middens.

An approach is suggested here to estimate past seasonal climate parameters using packrat midden assemblages and to offer insight into potential vegetation lag on a site-specific basis. This approach uses modern climate tolerances for conifer and shrub species (Thompson *et al*., 1999a, 1999b) and combines climographs (Dansereau, 1957; Hevly, 1988) and the Mutual Climatic Range (MCR) method (see Elias, 1997) to construct past climate envelopes. Climographs plot temperature versus precipitation. The MCR method estimates past climate based on fossil insect assemblages by graphing mean temperature of the warmest month versus the temperature range between the warmest and coldest months (Atkinson *et al*., 1986, 1987).

This climograph overlap approach, similar to the MCR method, establishes a climate envelope based on modern climatic tolerances (mean January and mean July temperature and precipitation) for each taxon in a midden assemblage and then estimates past January and July temperature and precipitation based on the overlap of the climate envelopes. This methodology may be used to infer past seasonal or annual climate from rodent middens worldwide, as long as adequate data on modern plant distributions and climate are available.

Thompson *et al*. (1999a, 1999b, 2000, in press) establish modern climate tolerances for conifer, hardwood, shrub, and monocot taxa that correspond to each taxon's entire known geographic range in North America. They used instrumental weather records from more than 8000 stations to develop a 25-km equal-area grid of modern climatic and bioclimatic parameters. Climatic parameters include monthly temperature and precipitation values and bioclimatic variables include mean temperature of the coldest month, growing degree days, and a moisture index. They digitized shrub and tree species from various range maps and determined the presence or absence of each species for each cell on this grid.

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Parameters for January and July temperature and precipitation from the continental-scale relations provided by Thompson *et al.* are used here to estimate seasonal temperature and precipitation from Holocene-age packrat middens from a site in northwestern Colorado.

Continental-scale data are more appropriate to estimate past climate than local data because a large database will encompass the end points of a particular taxon's climate distribution. These outliers may be more important than the mean because they could represent a combination of past climate and environmental variability that no longer occur in the modern world. Hence, using modern climate parameters from the entire geographic area of a taxon's range may represent past climate states better than using modern parameters from a local climate station, particularly because past parameters influencing species occurrence and distribution are not well understood. Finally, the methodology of selecting local weather stations at different elevations where a particular taxon is growing to estimate temperature and precipitation regressions restricts species to modern physiological, climatic, and site-specific factors that may not have occurred in the past.

SITE DESCRIPTION

Dinosaur National Monument (DNM) straddles the Colorado/Utah state line east of the Uintah Mountains approximately 30 km south of the Wyoming border. Elevations within the 854 km^2 monument range from 1443 to 2745 m and encompass a varied topography: mountains, plateaus, and steep, rocky canyons. Two major rivers, the Yampa and the Green, meet in approximately the center of the monument and flow to the southwest.

The vegetation in DNM includes elements from both the Great Basin and Rocky Mountain ecoregions with five major vegetation communities identified within the monument, grading from cold desert shrubland to montane forests (Kuntz *et al*., 1988). The most common plant community is pinyon/juniper (*Pinus edulis*/*Juniperus osteosperma*), occupying elevations from 1675 to 2440 m. Here, the understory is generally sparse. Sagebrush/grassland (*Artemisia*/Poaceae) communities are also common within the monument. Included in these assemblages are *Atriplex* spp., *Artemisia* spp., *Chrysothamnus* spp., and *Sarcobatus vermiculatus*. Douglas fir/ponderosa pine (*Pseudotsuga menziesii*/*Pinus ponderosa*) communities are found at higher elevations and are characterized by a sparse understory (often *Cercocarpus ledifolius, Symphoricarpos oreophilus*, and *Pachistima myrsinites*). *Pinus ponderosa* generally occupies the drier sites and *Pseudotsuga menziesii* grows on the steep-sloped, northern exposures (U.S. Department of Interior, 1986). The mountain shrub community includes *Amelanchier* spp., *Cercocarpus* spp., *Purshia tridentata*, *Artemisia* spp., *Symphoricarpos* spp., *Prunus virginiana, Ribes* spp., and *Populus tremuloides*. The last community, riparian, is found along the Yampa and Green river corridors and includes *Acer* spp., *Populus* spp., *Salix* spp., *Phragmites australis*, and *Juncus* spp.

Five midden samples (one modern, four fossil) were collected from a south-facing alcove, Sand Canyon Alcove, in upper Sand Canyon. The alcove, 1920 m in elevation, is located above the north side of the Echo Park Road approximately 8 km from its intersection with the Harpers Corner Road at 40°20′N latitude 109°01′W longitude. It is located in the Pennsylvanian/Permian-aged Weber sandstone, laid down roughly 290 million yr ago (Kuntz *et al*. 1988; Baars 2000). The dry alcove is shallow with a level floor; its width is approximately 15 m and depth from drip line to alcove back is 4.2 m. Numerous midden deposits are located in the crevices high along the back wall of the alcove.

METHODS

The fossil middens were scraped to remove the outer rind, weighed, disaggregated in distilled water for approximately 5 days, washed through a 20-mesh (0.84-mm) soil screen, and air dried. Plant remains were identified by matching with herbarium specimens, and individual taxa were assigned a relative abundance score after Van Devender (1973).

Although only four middens were radiometrically dated,[1] three of these middens provide a relatively high-resolution record of early Holocene vegetation. The midden assemblages represent two periods: early Holocene (9870 to 8460 ^{14}C yr B.P.) and late Holocene (3000 ^{14}C yr B.P. and modern). A total of 93 taxa from 13 families were identified (Sharpe, 1991). This paper uses the data from Sharpe (1991) to suggest a methodology using taxa recovered from packrat middens to estimate past temperature and precipitation.

RESULTS AND DISCUSSION

Vegetation Change

Pinyon/juniper woodland presently surrounds Sand Canyon Alcove and the dominant modern vegetation includes *Pinus edulis, Juniperus osteosperma, Cercocarpus montanus*, *Ephedra viridis, Opuntia polyacantha, Echinocereus triglochidiatus*, Asteraceae, and Poaceae. A more mesophytic vegetation (*Juniperus scopulorum, Ribes* spp., *Acer* spp., *Pseudotsuga menziesii, Pinus edulis*, and *Clematis ligusticifolia*) is located in the canyon drainage below and on the steep north-facing slope across from the alcove.

Conifers recovered from the midden assemblages indicate a transition from a cool/mesophytic to a warmer, more xerophytic community between 9050 and 8460 ^{14}C yr B.P. (Fig. 1). All three early Holocene middens contain *Juniperus scopulorum* and *Pinus flexilis*. *Juniperus osteosperma* first occurs in the 9050 ^{14}C yr B.P. midden. *Picea pungens, Juniperus communis, and Pinus flexilis* grew at least 215 m below their current range during this time. *Picea pungens*, *Juniperus communis*, and *Pseudotsuga*

[1] 9870 ± 80 ^{14}C yr B.P. (B-36809); 9050 ± 120 ^{14}C yr B.P. (B-36806); 8460 ± 100 ^{14}C yr B.P. (B-36808); 3000 ± 100 ^{14}C yr B.P. (B-36807). All material dated is *Neotoma* dung.

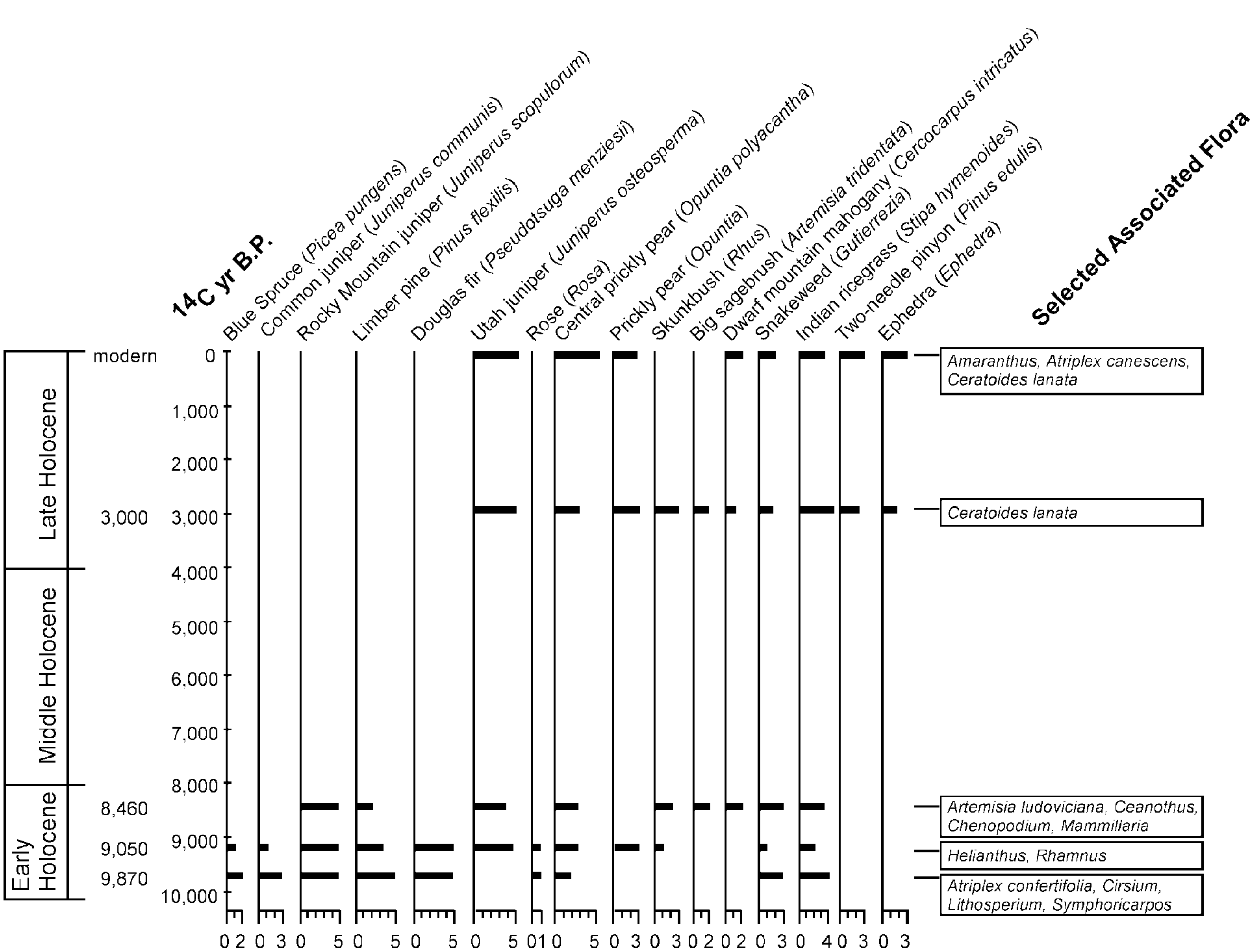

FIG. 1. Chronosequence of selected plant macrofossils and their relative abundance from Sand Canyon Alcove, Dinosaur National Monument, Colorado, elevation 1920 m. 1, rare (1 to 2 fragments); 2, uncommon (3 to 10 fragments); 3, common (11 to 50 fragments); 4, very common (51 to 100 fragments); and 5, abundant (more than 100 fragments). After Van Devender (1973).

menziesii disappear from the record before ca. 8460 ^{14}C yr B.P. *Picea pungens* and *Pinus flexilis* no longer occur within Dinosaur National Monument.

Shrubs occurring in the midden record also indicate climatic warming and drying during the early Holocene. Genera presently occupying more mesic sites (*Rhamnus* sp., *Symphoricarpos* sp., and *Rosa* sp.) are found only in the two older middens. Plants characteristic of more xeric environments are found by 8460 ^{14}C yr B.P. including *Artemisia ludoviciana, Cercocarpus* sp., and *Rhus* sp.

Evidence of a warming trend at Sand Canyon is supported by pollen and plant remains from nearby montane areas. At Snowbird Bog, 2470 m elevation, near Salt Lake City, Utah, pollen records indicate that the vegetation was predominantly alpine between 13,000 and 8000 ^{14}C yr B.P. After 8000 ^{14}C yr B.P. coniferous forest cover at the site increased, likely because of warmer summer and annual temperatures (Madsen and Currey, 1979). It is likely that the more xeric vegetation recorded at 8460 ^{14}C yr B.P. in Sand Canyon predates the xeric vegetation estimate for Snowbird Bog because Sand Canyon Alcove is lower in elevation, has a southern exposure, and was farther from glaciated terrain. At Swan Lake in southeastern Idaho (elevation 1563 m), a decrease in *Picea* sp. and *Abies* sp. and the appearance of *Cercocarpus* sp. and *Juniperus* sp. between approximately 10,300 to 8400 ^{14}C yr B.P. (Bright, 1966) also support increased aridity in the area at this time.

The modern pinyon/juniper woodland was in place before 3000 ^{14}C yr B.P. at this locale and all the taxa recorded 3000 yr ago are common near the alcove today. The late Holocene middens contained four taxa, *Gutierrezia* spp., *Lepidium* sp., *Opuntia polyacantha*, and *Stipa hymenoides*, persisting at this site from ca. 9870 ^{14}C yr B.P.

Climate Change

January and July temperature and precipitation values published by Thompson *et al.* (1999a, 1999b) for modern conifer and shrub taxa make it possible to evaluate past temperature and precipitation from plant remains recovered from packrat

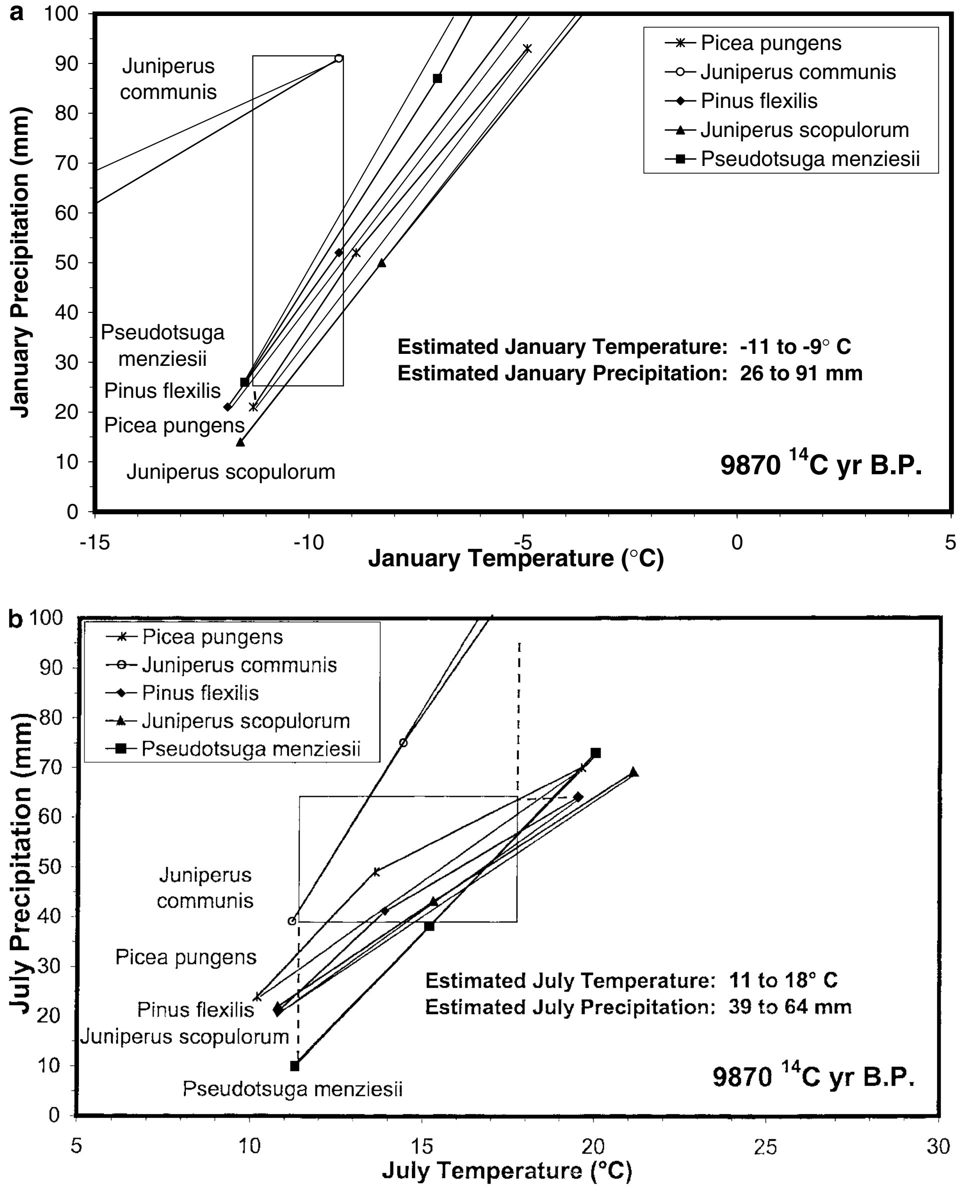

FIG. 2. Estimated past temperature and precipitation climograph overlap envelopes for selected plant taxa. Each point represents 10%, 50%, and 90% of each plant's cumulative occurrence relative to January or July temperature and precipitation. The lowest temperature and precipitation point is where 10% of the cumulative occurrence of the particular species is found and is located in the lower left portion of the graph. The next highest point (50%) is the median, or where the most likely occurrence of a taxon is found. The highest point in the upper right of the graph is where 90% of the cumulative occurrence of that particular species occurs. Placement of the climograph overlap envelopes for each midden assemblage was determined by selecting the most restricted values for both temperature and precipitation at 10% and 90% that encompassed all selected taxa. The lowest values at 90% and the highest values at 10% cumulative occurrence constrains the temperature and precipitation values as shown by dotted lines. "V" (Figs. 2e, 2f) represents temperature and precipitation at Vernal Airport, Utah, 1600 m elevation.

midden assemblages. Thompson *et al.* determined these cumulative occurrence values by noting the first occurrence of a taxon for a particular climate parameter (e.g., July temperature). This point was designated as 0%. Ten percent of the total number of occurrences of a species represents the climate parameter that corresponds with 10% of the cumulative occurrence of the species. Thompson *et al.* list 0, 10, 25, 50, 75, 90, and 100% of each plant's distribution relative to each particular climate parameter.

Climograph overlap envelopes for particular species are constructed herein using points representing 10%, 50%, and 90% of each specie's cumulative occurrence distribution relative to January or July temperature and precipitation (Figs. 2a–f). The 10–90% range for these graphs was chosen over the 0–100% range because it is likely a more realistic estimate of temperature and precipitation given the potential errors in modern climate estimates and taxa range maps (Thompson *et al.*, 1999a).

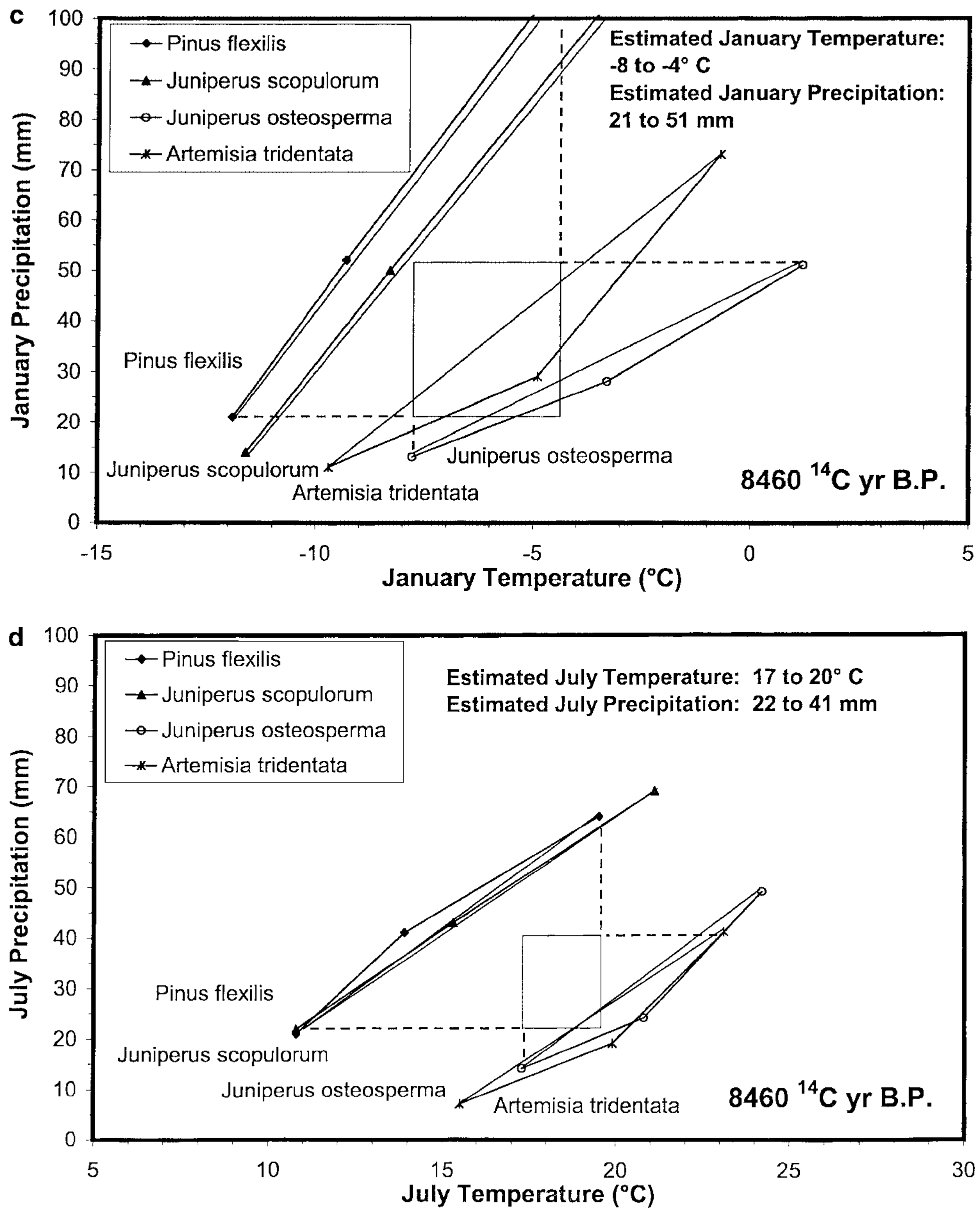

FIG. 2—*Continued*

Placement of the climograph overlap envelope for each midden was determined by selecting the most restricted values for both temperature and precipitation at 10 and 90% that encompassed all selected taxa. The lowest temperature and precipitation cumulative occurrence values at 90% and the highest temperature and precipitation cumulative occurrence values at 10% were used to determine the corners of each overlap envelope. Taxa were selected for graphing based solely on the inclusion of their climate parameters in Thompson *et al.* (1999a, 1999b, 1999c). Using this methodology, a general warming and drying trend (lowered effective moisture) is suggested for both summer and winter from the early Holocene to the late Holocene at Sand Canyon Alcove. This methodology also suggests a progression of extirpation and colonization for taxa at this locale over time.

Although *Juniperus communis* can tolerate much lower January temperatures than the other conifers shown, the overlapping January temperature range is fairly well constrained (−11° to −9°C) at 9870 ^{14}C yr B.P. among these five taxa using the climate envelope methodology outlined above (Fig. 2a). However, the January precipitation range for this time is not well constrained (26–91 mm). Note that the relation between temperature and precipitation among *Pseudotsuga menziesii, Pinus flexilis, Picea pungens*, and *Juniperus scopulorum* is fairly consistent in January (similar slope and clustered temperature and precipitation envelopes). Although the actual range of January precipitation values of *J. communis* (13–91 mm) overlaps the lower (10% range) precipitation values of these taxa, the relation (slope) of the temperature and precipitation

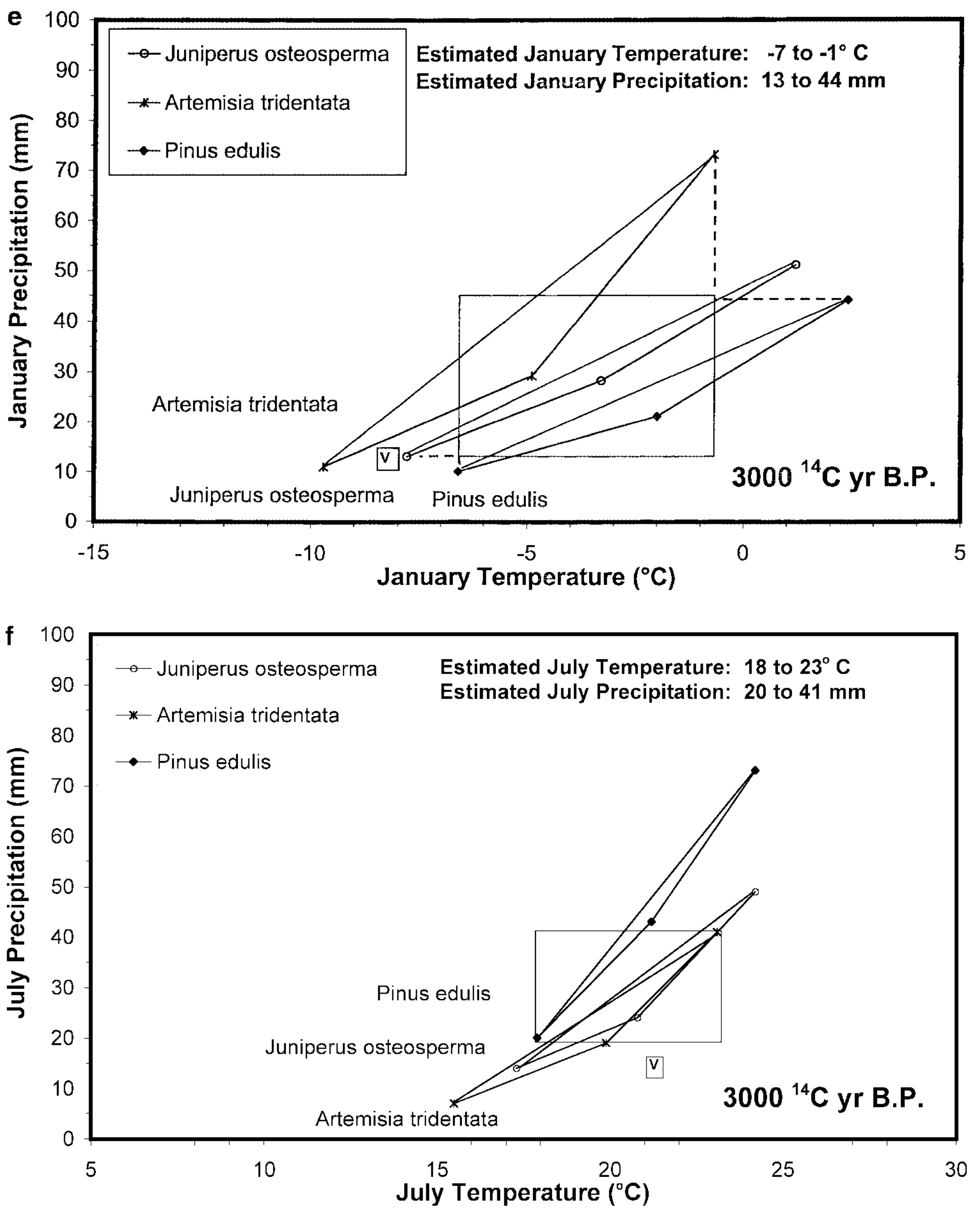

FIG. 2—*Continued*

parameters of *J. communis* is different from that of these other taxa.

A slightly better constrained 9870 ^{14}C yr B.P. July precipitation is suggested (39–64 mm), although the temperature and precipitation relation of *J. communis*, again, is different in slope when compared with other taxa (Fig. 2b). July temperature is less well constrained than January temperature and may have ranged between 11° and 18°C. *J. communis* drops out of the midden record between 9050 and 8460 ^{14}C yr B.P. Its overlap with other conifers on its high end (90% cumulative occurrence) in January and on its low end (10% cumulative occurrence) in July may indicate that *J. communis* became established at the site during cooler, wetter winters and/or wetter summers and may be persisting at this site during a trend toward decreasing early Holocene effective moisture.

Juniperus osteosperma and *Artemisia tridentata* first occur in the midden record sometime after 9870 and before 8460 ^{14}C yr B.P. The January and July climate envelopes of these taxa contain less effective moisture than the climate envelopes of *P. flexilis* and *J. scopulorum,* which were both present in the 9870 ^{14}C yr B.P. midden (Figs. 2c, 2d). January temperature and precipitation may have ranged between −8° and −4°C and 21 and 51 mm. July temperature and precipitation may have ranged between 17° and 20°C and 22 and 41 mm.

Again, as in the 9870 ^{14}C yr B.P. midden, the taxa show a temperature/precipitation climate envelope "split." It is possible

TABLE 1
Estimated Past Temperature and Precipitation

Date (^{14}C yr B.P.) and month	Temperature °C	Precipitation (mm)
9870 January	−11 to −9	26 to 91
8460 January	−8 to −4	21 to 51
3000 January	−7 to −1	13 to 44
Modern Vernal, Utah, January	−8	12
9870 July	11 to 18	39 to 64
8460 July	17 to 20	22 to 41
3000 July	18 to 23	20 to 41
Modern Vernal, Utah, July	21	14

Note. Sand Canyon Alcove, 40°20′N latitude, 109°01′W longitude, 1920 m elevation. Vernal Airport, 40°27′N latitude, 109°31′W longitude, 1600 m elevation. The Vernal Airport climate record is 72 yr long.

that the first occurrence taxa in this midden (*J. osteosperma* and *A. tridentata*) are representing a climate shift to a warmer and drier state and that *P. flexilis* and *J. scopulorum* are persisting relicts from the previous colder climate state. It is also possible that temperature and precipitation was variable, allowing all four species to thrive. Regardless, it is likely that a shift to less effective moisture allowed *J. osteosperma* and *A. tridentata* to become established in the area. *P. flexilis* and *J. scopulorum* are absent from both the remaining midden record and the modern vegetation list, suggesting that climatic or other environmental conditions changed enough so that they could no longer survive at the alcove.

Taxa in the 3000 ^{14}C yr B.P. midden are almost identical to taxa recovered from the modern midden and vegetation presently growing at, or near, the site today. This suggests that the climate at this time was similar to present. The occurrence of *Pinus edulis* in the midden record suggests increased January and July warming compared to the early Holocene (Figs. 2e, 2f). Temperature and precipitation estimates for January are −7° to −1°C and 13 to 44 mm, respectively. Temperature and precipitation estimates for July are 18° to 23°C and 20 to 41 mm.

Estimated January and July temperature and precipitation values for these three time periods at the alcove, 1920 m elevation, and the modern values (Western Regional Climate Center database) for Vernal, Utah, 1600 m elevation, are shown in Table 1. These are very general bounds to compare how the components of effective moisture may have decreased seasonally during the Holocene at this site. January and July temperatures increase from the early Holocene to modern and are consistent with the modern Vernal, Utah, temperature. Vernal experiences winter inversions because it is situated in a basin, so a January temperature lower than the estimated 3000 ^{14}C yr B.P. temperature is not surprising. The July temperature at Vernal is on the upper end of the estimated temperature range for 3000 ^{14}C yr B.P. at Sand Canyon. This is consistent because Vernal is 320 m lower in elevation than Sand Canyon Alcove. Precipitation at Vernal is lower in both January and July compared to the estimated precipitation at 3000 ^{14}C yr B.P., again reflecting Vernal's lower elevation relative to Sand Canyon Alcove.

Comparing the modern Vernal temperatures with estimated temperatures at 9870 ^{14}C yr B.P. suggest that Sand Canyon Alcove may have been at least 1° to 3°C colder in January and no greater than 3° to 10°C colder in July than at present. Precipitation at 9870 ^{14}C yr B.P. may have been at least 2 times modern in January and approximately 3 times modern in July.

With additional taxa included in the Thompson *et al*. database for Alaska (Thompson *et al*., in press) and databases constructed for other areas of the world, more refined estimates of past effective moisture and seasonal temperature and precipitation should be possible. If the modern temperature and precipitation parameters for specific taxa remained constant through time, discrepancies or "splits" in January and July temperature and precipitation estimates based on vegetation may show both the persistence of relict vegetation and the first occurrence taxa responding to a climate shift. Questions that might be pursued in future research include the following: 1) how can we determine if middens contain relict, persisting, and first-occurrence taxa; 2) do other midden data show splits in temperature and precipitation among taxa; and 3) if so, can these splits be tracked temporally, geographically, and taxonomically? If data from additional studies support this concept, general estimates of temperature and precipitation based on entire midden assemblages may need to be viewed in light of both relict and first occurrence taxa.

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