

Paleoecology on the Colorado Plateau

Introduction

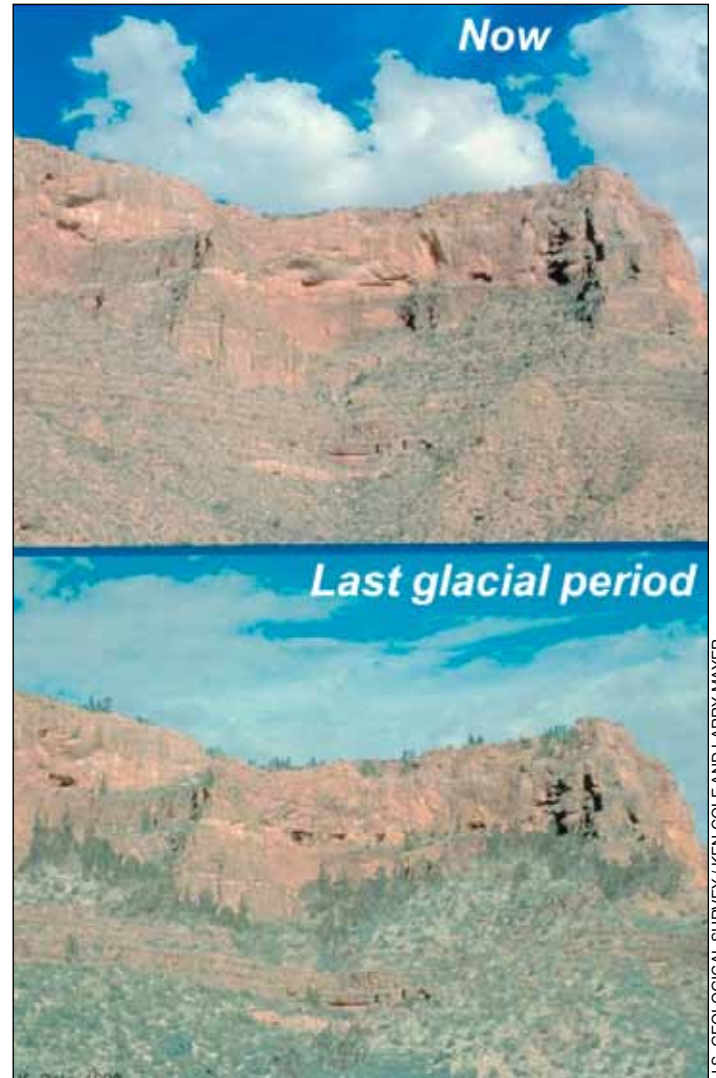
Paleoecologists study the interactions among ancient organisms and their environments. The records they collect provide a long-term perspective on how an ecosystem has developed, showing how environmental influences, like climate, fire, and humans, have shaped the ecosystem through time. This long-term perspective is necessary because some ecological phenomena take centuries to run their courses; for example, although the last glacial period ended about 11,000 years ago, some plant species still appear to be migrating back into the territories they occupied before the glaciers advanced. In addition, paleoecological records help ecologists determine how human impacts to ecosystems have changed natural patterns and how ecosystems can be restored. Ecologists have been recording data on climate and vegetation for less than a century, so in order to reconstruct what happened before that time, paleoecologists must interpret the clues recorded in packrat middens, lake and bog sediments, and tree rings. On the Colorado Plateau, these records provide rich data on ecosystem development during and after the most recent glacial period.

Records Used to Reconstruct the Past

In the Southwest, three major types of records are used to reconstruct the history of ecosystem development over the last 50,000 years: packrat middens, lake and bog sediments, and tree rings.

Packrat Middens

The garbage piles of packrats provide snapshots of the vegetation growing around a particular site at a particular time in the past. Each midden is a cache of leaves, seeds, fruits, twigs, pollen, bones, shells, and reptile scales that a packrat has collected. To build the midden and mark its territory, the packrat often urinates on the midden, which hardens the plant parts, along with any plant pollen that deposited on it. In the dry Southwest, these hardened middens remain preserved in rock crevices and cliff walls for thousands of years. The result is a collection of extremely well-preserved plant fossils that can be identified to species (Cole 2008). While packrat middens have been invaluable in understanding how vegetation has changed in the Southwest over time, they do have a few



U.S. GEOLOGICAL SURVEY / KEN COLE AND LARRY MAYER

The desert scrub that grows along the Grand Canyon today (top) is very different from the vegetation that existed during the last glacial period (bottom). Paleoecologists reconstructed what the past vegetation would have looked like from the fossils in the packrat middens they found along this cliff.

disadvantages as evidence of past vegetation: (1) the fossils in packrat middens only reveal a definite presence of a species, but not an absence; (2) since packrats only tend to collect within 65 to 150 feet of their midden, the packrat middens provide only a local record of vegetation; and (3) many middens must be collected over a broad spatial area to reconstruct the vegetation across the whole landscape (Cole 2008).





W. G. SPAULDING

Packrat middens can usually be found in rock ledges and dry caves. In the Southwest, they can stay preserved for at least 50,000 years.

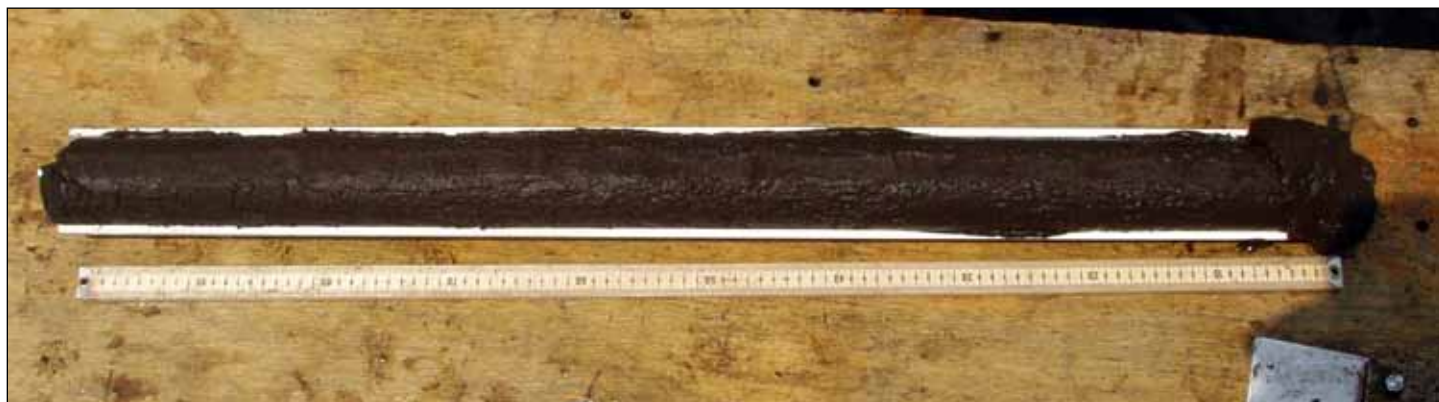
Lake and Bog Sediments

In contrast to packrat middens, lake and bog sediments provide a continuous record of vegetation and fire near one site. The vegetation history is reconstructed from the pollen and the plant parts preserved in the sediment at the bottom of the lake. Each year, pollen, plant litter, and small bits of charcoal fall to the bottom of the lake and become covered with sediment and preserved. Over time, this sediment builds into one long

record of environmental change. Paleoecologists then extract a core of the sediment and sample it at small intervals to count and identify pollen, plant fossils, and charcoal. The history of the vegetation growing near the lake or bog is reconstructed mostly from the pollen, which has a few disadvantages as a record of vegetation; namely that it cannot always be identified to species and is produced in abundance by some species, but not others. The record is supplemented by the plant fossils, which help confirm that a specific species was growing near the site. But, like the vegetation record provided by packrat middens, a presence of fossil pollen or plant parts only reveals the presence of a taxa, not an absence. The charcoal record in the lake sediment provides a history of local and regional fires, but because it is influenced by the processes of transport and deposition, it is not as straightforward to interpret as the fire history derived from tree rings (Whitlock and Larsen 2001). However, charcoal records often extend much further into the past.

Tree Rings

Tree rings records are used to reconstruct climate history, fire history, insect outbreaks, and the age structure of forests. Because trees add a new ring to their trunks each year, each ring can be easily dated. Tree rings provide an accurate record of annual precipitation because the rings grow in proportion to the amount of rain in a given year. The width of the ring is a proxy for the precipitation amount that year. Likewise, tree rings also provide accurate histories of fire and insect outbreaks from fire scars left on the rings and from tell-tale patterns of narrow tree-rings caused by the stress of defoliation by insects. Finally, just by dating the age of many trees across a landscape, ecologists can reconstruct when different patches of forest developed and what year trees established at a particular location.



Cores of lake mud are usually collected one meter at a time and stored for later analysis. This particular section of core contains a 2,000 year vegetation record in the millions of fossilized pollen grains stored in the mud.

Vegetation History on the Colorado Plateau

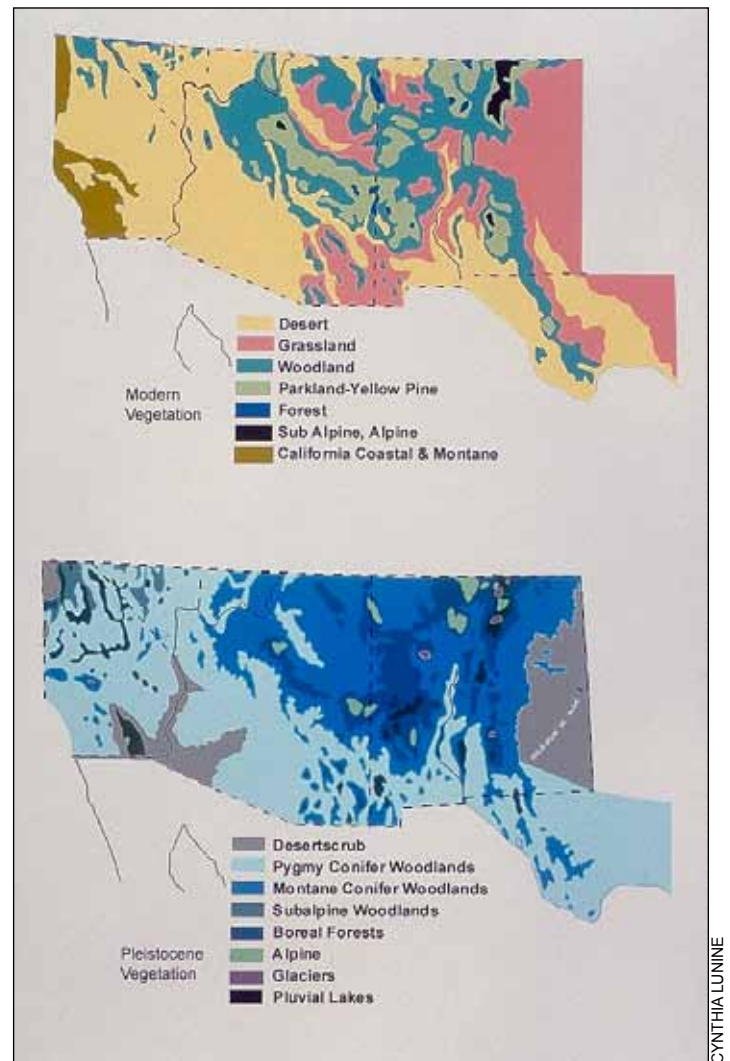
The most recent glacial period, the Wisconsin glacial period, lasted from about 100,000 to 11,000 years ago. A detailed vegetation record on the Colorado Plateau starts 50,000 years ago and continues through the time when the glaciers most recently reached their maximum extent, the end of the glacial period, and the relatively warm period of the last 11,600 years, known as the Holocene.

In general, individual plant species responded to the colder climates of the glacial period by shifting their distributions to lower elevations (Coats et al. 2008). However, each species responded to changing climate in a unique way, leading to vegetation compositions unlike those that exist today (Cole 1990).

Vegetation During the Last Glacial Period

On the Colorado Plateau, the oldest dated packrat middens are 50,000 years old, which corresponds to the middle of the most recent glacial period. Although no continental glaciers covered the Southwest, as they did over Canada and the northern United States, the highest elevations on the Colorado Plateau were probably covered with ice (Anderson et al. 2000). Between about 50,000 and 27,500 years ago, temperatures have been estimated to be about 5 to 7°F colder than they are today on the southern Colorado Plateau. During this time, the packrat midden records suggest that high elevation forests consisted of limber (*Pinus flexilis*) or bristlecone pines (*Pinus aristata*) mixed with Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), perhaps with sagebrush (*Artemisia* spp.) growing in the forest openings. Along the Mogollon Rim, an open forest of Engelmann spruce, white fir (*Abies concolor*), Douglas fir (*Pseudotsuga menziesii*), and sagebrush may have existed. Between 5,000 and 1,500 feet in the Grand Canyon, a juniper-desertscrub association of Utah juniper (*Juniperus osteosperma*) and single-seed juniper (*Juniperus monosperma*), sagebrush, prickly pear cactus (*Opuntia* spp.), and agave (*Agave* spp.) existed, with saltbush (*Atriplex* spp.) at the lowest elevations (Anderson et al. 2000).

After about 27,500 years ago, glaciers started to advance again worldwide, reaching their maximum extent about 21,000 years ago. Before that time, the vegetation composition along the Mogollon Rim remained similar to what it was during the earlier period, but after the full glacial maximum, a closed Engelmann spruce forest developed. Between 5,200 and 6,900 feet in elevation, a mixed conifer forest of limber pine, white fir, and Douglas fir, with associates of Utah juniper, sagebrush, rosaceous shrubs, agave, and prickly-pear, grew. Below 4,500



A comparison of modern vegetation with vegetation during the last glacial period. Notice that ponderosa pine forest (labeled “parkland-yellow pine” on the modern vegetation map), a common forest type today, did not exist at all on the Colorado Plateau during the last glacial period.

feet, Utah and single-seed juniper mixed with sagebrush, shadscale (*Atriplex confertifolia*), and Mormon tea (*Ephedra viridis*) (Anderson et al. 2000). Species characteristic of cool and wet areas moved into elevations at 3,750 feet in the eastern Grand Canyon, including Rocky Mountain maple (*Acer glabrum*), common juniper (*Juniperus communis*), gooseberry (*Ribes pinetorum*), and hop hornbeam (*Ostrya knowltonii*) (Coats et al. 2008).

Towards the end of the glacial period, at around 14,000 years before present, major reorganizations of the vegetation started to occur (Anderson et al. 2000). For example, at three high elevation sites—two on the highest parts of the Kaibab Plateau and one in the Jemez Mountains—the tundra that had existed

14,000 years ago had been replaced by forests with compositions similar to modern forests by 10,000 years ago (Weng and Jackson 1999, Anderson et al. 2008).

Vegetation During the Holocene

At the start of the Holocene, about 11,700 years ago, the climate warmed rapidly, increasing by about 7°F over less than a century (Cole 2009). With this shift in climate came a major change in the vegetation make-up of the Colorado Plateau. Prior to 10,400 years ago, no fossils of ponderosa pine (*Pinus ponderosa*) had been found on the Colorado Plateau, despite its wide distribution across the region today. Scientists are unsure why, but posit that either not enough fires occurred to maintain a ponderosa pine forest or chilly late summers did not allow for tree growth and recruitment (Anderson et al. 2000). But after 10,400 years ago, environmental conditions allowed ponderosa pine to expand rapidly across the southern Colorado Plateau (Anderson 1993).

After this initial warm-up, the climate and vegetation compositions remained relatively stable through the rest of the Holocene, except perhaps during the middle Holocene, which may have been warm and dry. However, the exact dates of this dry period vary widely among sites (Anderson 1993, Hasbargen 1994, Weng and Jackson 1999, Anderson et al. 2008). Some species, like pinyon pine (*Pinus edulis*), took longer to migrate into their present ranges than other species. But overall, vegetation composition did not change very much throughout the Holocene until about 150 years ago, when more intensive uses of the landscape began to alter ecosystem properties.

Applications to Natural and Cultural Resource Management

Insects Outbreaks

Because major insect outbreaks tend to occur decades apart, the causes of the outbreaks are difficult to determine without a long-term record. Using tree-rings from affected trees, paleoecologists have been able to reconstruct a history of western spruce budworm (*Choristoneura occidentalis*) outbreaks in the Southwest. They have found that the outbreaks occur in a pseudoperiodic pattern, usually during years with above normal spring precipitation. In the Jemez Mountains in northern New Mexico, more widespread and intense outbreaks occurred in the late 20th century, likely due to land use practices that allowed the growth of host trees (Swetnam and Lynch 1993). However, in the San Juan and Sangre de Cristo mountains in southwestern Colorado, outbreaks did not increase in severity during the 20th century, despite a documented history of human impacts (Ryerson et al. 2003).

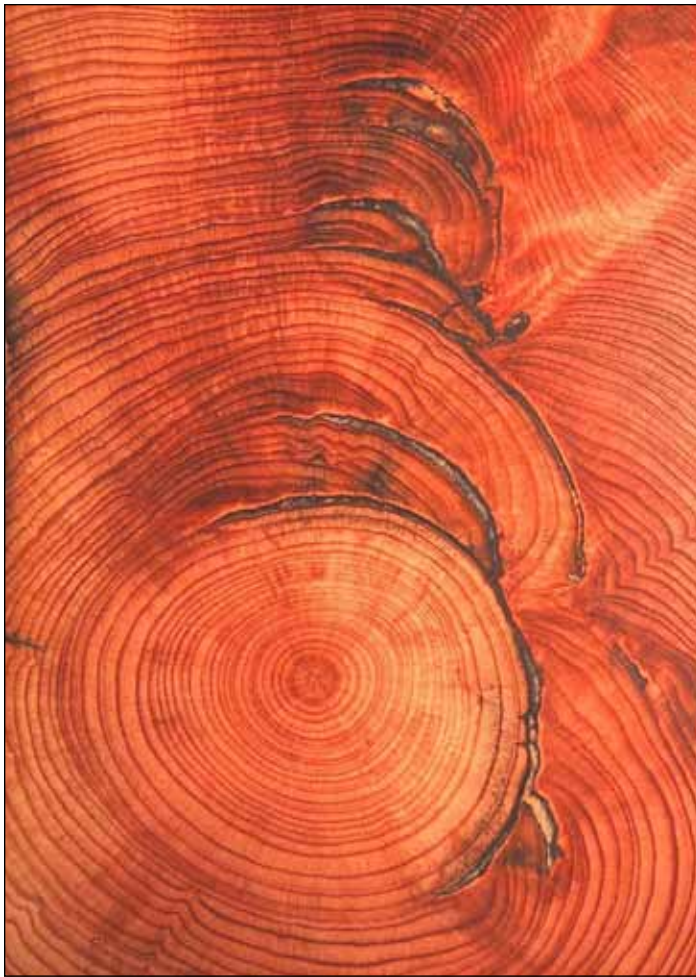
Fire Histories

The Southwest has the longest and most-detailed record of fire histories derived from tree rings in the world (Swetnam and Baisan 1996, Swetnam and Betancourt 1998). Ecologists have used these fire histories to understand the natural fire regimes for different vegetation types and how those regimes are influenced by climate and land use. They have found that prior to the year 1900, some years had remarkably synchronous fires across the region (Swetnam and Baisan 1996). After the start of intensive livestock grazing across the region and the beginning of organized fire suppression efforts, the occurrence of fires dropped precipitously and shifts in forest composition occurred (Swetnam and Baisan 1996, Mast and Wolf 2004, Fulé et al. 2009).

Compiling fire histories from different types of vegetation has shown that the frequency and severity of fires varies widely across vegetation types. For example, ponderosa pine forests typically experienced frequent, low severity fires that were limited by fuel availability (Schoennagel et al. 2004). Fires in these forests across the region tended to occur in a dry year that was preceded by wet years (Swetnam and Betancourt 1998). In contrast, mixed-conifer forests typically experienced both low severity fires and infrequent stand-replacing fires (Schoennagel et al. 2004). Fires in these forests tended to occur during drought years (Swetnam and Betancourt 1998). The expanding understanding of how fire differs across vegetation types has shown that a one-size-fits-all approach to managing forests with fire might not be the most appropriate policy for fire management (Schoennagel et al. 2004).

Land Use

Paleoecology can provide insight into the causes and consequences of environmental change in the Southwest. While human impacts are usually assumed to have begun with settlement in the mid to late 1800s, paleoecological data provides evidence that cultures before that time also modified the environment. At Chaco Canyon, a major cultural center built between the 800s and the 1200s, more than 200,000 trees were logged and carried from isolated mountaintops more than 45 miles away in order to construct the great houses (Betancourt et al. 1986, English et al. 2001). Many of the trees used were of the same size class, which suggests that the Chacoans selectively harvested the trees, rather than clear-cutting the forests (Betancourt et al. 1986). However, the Chacoan culture may have had more lasting effects on the pinyon and juniper populations in the canyon. The packrat midden record shows that pinyon and juniper populations dramatically declined around A.D. 1000, and they have yet to recover (Betancourt and Van Devender 1981). Most likely, wood cutting for fuel for the



Fire scars, like the ones on this ponderosa pine tree stump, allow paleoecologists to understand how intensive land use and fire suppression have changed natural fire regimes.

growing population eradicated the pinyon-juniper woodlands (Betancourt and Van Devender 1981). Similarly, in southwestern Colorado, records of fuel use indicate that Ancestral Puebloan people living there from A. D. 750 to 900 significantly altered the landscape through burning, clearing, and harvesting local pinyon and juniper for building and for fuel (Kohler and Matthews 1988).

Although humans did impact the environment in the more ancient past, many of the current critical resource issues in the Southwest can be traced to the settlement of the Colorado Plateau in the mid to late 1800s. The effects of grazing and fire suppression can be studied by comparing pre-settlement records to post-settlement ones. At Glen Canyon National Recreation Area, a comparison of packrat middens from before the introduction of livestock to modern middens from grazed and ungrazed areas showed that grazing reduced the plant biodiversity and the number of native plants (Fisher et al. 2009).

Grazing has also altered fire regimes. In numerous fire history studies across the Southwest, fires became much less frequent after the onset of grazing, especially by sheep, and organized fire suppression (e.g. Savage and Swetnam 1990, Touchan et al. 1996, Mast and Wolf 2004, Fulé et al. 2009). Only in rare locations that did not experience grazing or fire suppression, like the kipuka “islands” in El Malpais National Monument, did fire regimes stay the same through the 19th and 20th centuries (Touchan et al. 1996). The legacy of this drastic reduction in fire frequency after settlement can still be seen today in the forests in the region. For example, in both southwestern Colorado and on the north rim of the Grand Canyon, the composition shifted from dominance by ponderosa pine to dominance by white fir, and the mixed-conifer forest became denser, at least at first. (Fulé et al. 2009, Mast and Wolf 2004). A recent study found that mixed-conifer forests on the north rim were densest in the decades after fire suppression began, but in the middle of the 20th century, density started to decrease—showing that the legacy of fire suppression may be more complex than previously thought (Vankat, in review).

Restoration

Paleoecology can help guide restoration by showing whether the functioning of a particular ecosystem is inside a range of natural variability or not and by providing reference conditions for restoration along a spectrum of environmental pressures. As an example, prior to studies of fire history in ponderosa pine forest, ecologists did not know that surface fires frequently occurred in ponderosa pine and mixed conifer forests before intensive grazing began in the 1880s (Swetnam et al. 1999). Now, prescribed fire is frequently used to restore these forests to a more natural state. However, from other paleoecological studies of the Southwest, ecologists have noted that restoring a system to its “pre-disturbance” or “pre-European settlement” state does not always make ecological sense (Millar and Brubaker 2006). Restoring a system to a “pre-European” reference condition assumes that humans did not influence the ecosystem prior to the arrival of settlers and that the climate at that time was the same as it is today. But, in the West, for example, research on ancient cultures shows that humans did influence their environment before the 1800s, and the period between 1840 and 1860 coincided with the coldest part of the Little Ice Age (a chilly period between the 15th and 19th centuries), which makes “pre-settlement” conditions a poor model for a restored ecosystem (Millar and Brubaker 2006). In addition, many of the current disturbances affecting natural systems, like invasive species and elevated carbon dioxide, are one-way changes that will not allow a system to revert to some pre-disturbance state (Cole 2009), and some processes that have been occurring since settlement, like the

expansion and infill of pinyon and juniper, are being driven by both natural and human impacts (Shinneman and Baker 2009). Because of all these confounding influences currently acting upon ecosystems, paleoecologists have suggested that instead of restoring a system to a specific point in time, ecosystems should be realigned to a state that is within a range of historic conditions so that they would then be resilient to ongoing change, like climate change (Millar and Brubaker 2006, Swetnam et al. 1999). Paleoecological studies help determine that natural range of variability.

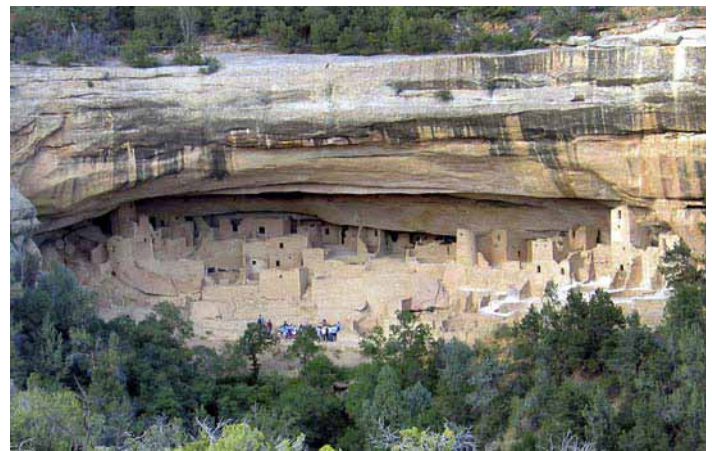
Climate Change

By showing how plants have responded to climate change in the past, paleoecological data helps ecologists understand how vegetation might respond to future climate change over the long-term. However, while paleoecological studies can caution and illustrate how changes in climate might affect ecosystems, they cannot be used to predict exact responses to future climate. Ecosystems are complex systems that are reacting to previous disturbances, recent human impacts, and a climate that is variable over many time scales (Jackson et al. 2009). Paleoecological data can instead give ecologists a sense of landscape-scale vegetation responses to climate over long periods of time.

One insight taken from paleoecology in the Southwest is that plants respond as individuals to changes in climate, instead of migrating as whole intact communities (Graham and Grimm 1990). As a result, plant communities unlike any that exist today will likely occur in the future (Williams and Jackson 2007). In addition, vegetation in a particular place is not necessarily in equilibrium with the current climate; instead, the distribution of some plants may lag behind changes in climate by thousands of years (Cole 2009). For example, pinyon pine and Utah juniper appear to have arrived at the current northern edges of their ranges within the last millennia (Betancourt et al. 1991, Lyford et al. 2003). Packrat midden records in the Southwest have also shown that after a major change in climate, the resulting vegetation shifts can persist for thousands of years after the event, as slow-colonizing species take time to establish and grow (Cole 2009).

Anthropology and Archaeology

Paleoecology is just one tool that anthropologists can use to understand the social dynamics of ancient Puebloan civilizations. The density of both archaeological and paleoecological sites on the southern Colorado Plateau makes it a unique place for studying interactions between humans and the environment (Dean et al. 1985). When both kinds of data are available, anthropologists can, for example:



Paleoecological records can help anthropologists determine if environmental changes caused the ancient Puebloan people to leave their major cultural centers, like the cliff dwellings in Mesa Verde National Park.

- Count the number of tree-rings in ancient timbers to determine the age of buildings (Douglass 1926)
- Compare precipitation records to settlement and immigration patterns (Towner 2002)
- Analyze fossil pollen to determine the diet and health of ancient Pueblos (Reinhard et al. 2006)
- Estimate maize and bean production from drought records in tree rings (Varien et al. 2007)
- Understand forest harvesting practices, based on the number, size, and age of timbers, and their isotopic composition, which tells researchers where people logged the timbers (English et al. 2001)

In the most famous example of applying paleoecological data to an anthropological problem, anthropologists had speculated that the severe droughts of the late 13th century caused the abandonment of the major cultural centers on the Colorado Plateau. However, more recently, anthropologists have argued that societies are not so simple that a change in climate necessarily precipitates abandonment (Dean et al. 1985). A variety of other factors, such as conflict, ideological changes, and the attractiveness of regions to the south, could have influenced the decision to move away from the cliff dwellings and great houses (Nelson and Schachner 2002). These examples show that while interpreting the reasons for complex human behavior is difficult, using paleoecological methods can still help anthropologists understand some aspects of past culture and society.

Literature Cited

- Anderson, R. S. 1993. A 35,000 year vegetation and climate history from Potato Lake, Mogollon Rim, Arizona. *Quaternary Research* 40:351-359.
- Anderson, R. S., J. L. Betancourt, J. I. Mead, R. H. Hevly, and D. P. Adam. 2000. Middle- and late-Wisconsin paleobotanic and paleoclimatic records from the southern Colorado Plateau, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology* 155:31-57.
- Anderson, R. S., R. B. Jass, J. L. Toney, C. D. Allen, L. M. Cisneros-Dozal, M. Hess, J. Heikoop, and J. Fessenden. 2008. Development of the mixed conifer forest in northern New Mexico and its relationship to Holocene environmental change. *Quaternary Research* 69:263-275.
- Betancourt, J. L., and T. R. Van Devender. 1981. Holocene vegetation in Chaco Canyon, New Mexico. *Science* 214:656-658.
- Betancourt, J. L., J. S. Dean, and H. M. Hull. 1986. Prehistoric long-distance transport of construction beams, Chaco Canyon, New Mexico. *American Antiquity* 51(2): 370-375.
- Betancourt, J. L., W. S. Schuster, J. B. Mitton, and R. S. Anderson. 1991. Fossil and genetic history of a pinyon pine (*Pinus edulis*) isolate. *Ecology* 72(5): 1685-1697.
- Coats, L. L., K. L. Cole, and J. I. Mead. 2008. 50,000 years of vegetation and climate history on the Colorado Plateau, Utah and Arizona, USA. *Quaternary Research* 70:322-338.
- Cole, K. 2008. Prehistoric packrats piled up clues to climate change. USGS Fact Sheet 2008-3053, United States Geological Survey, Flagstaff, AZ.
- Cole, K. L. 2009. Vegetation response to early Holocene warming as an analog for current and future changes. *Conservation Biology* 24(1): 29-37.
- Dean, J. S., R. C. Euler, G. J. Gumerman, F. Plog, R. H. Hevly, and T. N. V. Karlstrom. 1985. Human behavior, demography, and paleoenvironment on the Colorado Plateaus. *American Antiquity* 50(3): 537-554.
- Douglas, A. E. 1929. The secret of the Southwest solved by talkative tree rings. *National Geographic Magazine* 56: 736-770.
- English, N. B., J. L. Betancourt, J. S. Dean, and J. Quade. 2001. Strontium isotopes reveal distant sources of architectural timber in Chaco Canyon, New Mexico. *Proceedings of the National Academy of Sciences* 98(21) 11891-11896.
- Fisher, J., K. L. Cole, and R. S. Anderson. 2009. Using packrat middens to assess grazing effects on vegetation change. *Journal of Arid Environments* 73:937-948.
- Fulé, P. Z., J. E. Korb, and R. Wu. 2009. Changes in forest structure of a mixed conifer forest, southwestern Colorado, USA. *Forest Ecology and Management* 258:1200-1210.
- Graham, R. W., and E. C. Grimm. 1990. Effects of global climate change on the patterns of terrestrial biological communities. *Trends in Ecology and Evolution* 5(9): 289-292.
- Hasbargen, J. 1994. A Holocene paleoclimatic and environmental record from Stoneman Lake, Arizona. *Quaternary Research* 42:188-196.
- Jackson, S. T., J. L. Betancourt, R. K. Booth, and S. T. Gray. 2009. Ecology and the ratchet of events: climate variability, niche dimensions, and species distributions. *Proceedings of the National Academy of Sciences* 106(2): 19685-19692.
- Kohler, T. A., and M. H. Matthews. 1988. Long-term Anasazi land use and forest reduction: a case study from southwest Colorado. *American Antiquity* 53:537-564.
- Lyford, M. E., S. T. Jackson, J. L. Betancourt, and S. T. Gray. 2003. Influence of landscape structure and climate variability on a late Holocene plant migration. *Ecological Monographs* 73(4): 567-583.
- Mast, J. N., and J. J. Wolf. 2004. Ecotonal changes and altered tree spatial patterns in lower mixed-conifer forests, Grand Canyon National Park, Arizona, U.S.A. *Landscape Ecology* 19:167-180.
- Millar, C. I., and L. B. Brubaker. 1996. Climate change and paleoecology: new contexts for restoration ecology. Pages 315-340 in D. A. Falk, M. A. Palmer, and J. B. Zedler, editors. *Foundations of restoration ecology*. Island Press, Washington, D. C.
- Nelson, M. C., and G. Schachner. 2002. Understanding abandonments in the North American Southwest. *Journal of Archaeological Research* 10(2): 167-206.
- Reinhard, K. J., S. Edwards, T. R. Damon, and D. K. Meier. 2006. Pollen concentration analysis of Ancestral Pueblo dietary variation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 237:92-109.
- Savage, M., and T. W. Swetnam. 1990. Early 19th-century fire decline following sheep pasturing in a Navajo ponderosa pine forest. *Ecology* 71:2374-2378.
- Schoennagel, T., T. T. Veblen, and W. H. Romme. 2004. The

- interaction of fire, fuels, and climate across Rocky Mountain forests. *BioScience* 54:661-676.
- Shinneman, D. J., and W. L. Baker. 2009. Historical fire and multidecadal drought as context for pinon-juniper woodland restoration in western Colorado. *Ecological Applications* 19(5): 1231-1245.
- Swetnam, T. W., and A. M. Lynch. 1993. Multicentury, regional-scale patterns of western spruce budworm outbreaks. *Ecological Monographs* 63:399-424.
- Swetnam, T. W., and C. H. Baisan. 1996. Historical fire regimes patterns in the southwestern United States since AD 1700. Pages 153-156 in J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto, editors. *Symposium on Fire in Wilderness and Park Management*, March 30-April 1, 1993. USDA Forest Service General Technical Report INT-320, Missoula, MT.
- Swetnam, T. W., and J. L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate* 11:3128-3147.
- Swetnam, T. W., C. D. Allen, and J. L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9:1189-1206.
- Toney, J. L., and R. S. Anderson. 2006. A postglacial palaeoecological record from the San Juan Mountains of Colorado USA: fire, climate and vegetation history. *The Holocene* 16:505-517.
- Touchan, R., T. W. Swetnam, and H. D. Grissino-Mayer. 1996. Effects of livestock grazing on pre-settlement fire regimes in New Mexico. Pages 268-272 in J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto, editors. *Symposium on Fire in Wilderness and Park Management*, March 30-April 1, 1993. USDA Forest Service General Technical Report INT-320, Missoula, MT.
- Towner, R. H. 2002. Archeological dendrochronology in the southwestern United States. *Evolutionary Anthropology* 11: 68-84.
- Van Devender, T. R., and W. G. Spaulding. 1979. Development of vegetation and climate in the southwestern United States. *Science* 204.
- Vankat, J. 2010. Post-1935 changes in mixed conifer, spruce-fir, and quaking aspen forests of Grand Canyon National Park, Arizona, USA. *Forest Ecology and Management*, in review.
- Varien, M. D., S. G. Ortman, T. A. Kohler, D. M. Glowacki, and C. D. Johnson. 2007. Society for American Archaeology 72(2): 273-299.
- Weng, C., and S. T. Jackson. 1999. Late glacial and holocene vegetation history and paleoclimate of the Kaibab Plateau, Arizona. *Palaeogeography, Palaeoclimatology, Palaeoecology* 153:179-201.
- Whitlock, C., and C. Larsen. 2001. Charcoal as a fire proxy. Pages 75-97 in Smol, J. P., H. J. B. Birks, and W. M. Last, editors. *Tracking environmental change using lake sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators*. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Williams, J. W., and S. T. Jackson. 2007. Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and Environment* 5(9): 475-482.