Changes in Frost Frequency and Desert Vegetation Assemblages in Grand Canyon, Arizona

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Abstract: The effect of decreasing frost frequency on desert vegetation was documented in Grand Canyon by replication of historical photographs. Although views by numerous photographers of Grand Canyon have been examined, 400 Robert Brewster Stanton and Franklin A. Nims views taken in the winter of 1889-1890 provide the best information on recent plant distribution. In Grand Canyon, where grazing is limited by the rugged topography, vegetation dynamics are controlled by climate and by demographic processes such as seed productivity, recruitment, longevity and mortality. The replicated photographs show distribution and abundance of several species were limited by severe frost before 1889. Two of these, brittlebush *(Encelia farinosa)* and barrel cactus *(Ferocactus cylindraceus)*, have clearly expanded their ranges up-canyon and have increased their densities at sites where they were present in 1890. In 1890, brittlebush was present in warm microhabitats that provided refugia from frost damage. Views showing desert vegetation in 1923 indicate that *Encelia* expanded rapidly to near its current distribution between 1890 and 1923, whereas the expansion of *Ferocactus* occurred more slowly. The higher frequency of frost was probably related to an anomalous increase in winter storms between 1878 (and possibly 1862) and 1891 in the southwestern United States.

The distributional limits of many desert plants may be determined by unusual climatic conditions. Because many of the columnar cacti and leguminous shrubs and trees that characterize the Sonoran Desert are sensitive to frost, the northern limits of that desert have been defined in terms of frost frequency (Shreve 1911; Turnage and Hinckley 1938; Hastings 1963). Rare, catastrophic freezes may cause widespread mortality of Sonoran Desert plants (Turnage and Hinckley 1938; Bowers 1981), particularly seedlings or juveniles not protected by nurse plants (Niering *et al* 1963).

Desert plant assemblages are also sensitive to grazing by domestic livestock. Grazing is so pervasive across the North American desert that it is often difficult to separate the effects of climate from those of grazing. For instance, domestic livestock grazing has been blamed for widespread conversion of grasslands to shrublands (Bahre 1991) and promotion of exotic or unpalatable species (Burgess *et al* 1991), although climatic variability or change could have been responsible for many of the changes (Hastings and Turner 1965). Sites that have been protected from grazing typically are small and relatively inaccessible (*eg*, Schmutz *et al* 1976; Turner 1990).

Large tracts of ungrazed desert are extremely rare; rarer still are those where vegetation has been or can be monitored for many decades. One such area is the bottom of Grand Canyon, where impassable cliffs

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prevent movement of grazing animals, and spectacular scenery has encouraged a rich history of photography useful in reconstructing past vegetation (Figure 1). Over the past several years, we have replicated hundreds of historical photographs. This paper reports on changes in desert vegetation that have been documented by matched views.

Photography was extremely important to early river runners, who wanted to document their exploits or finance their expeditions by selling photographs (Fowler 1989). Photographers on early Grand Canyon explorations included Jack Hillers of Major John Wesley Powell's second expedition (1872); Timothy O'Sullivan and William Bell of the Wheeler Expedition (1871-73); Ben Wittick, who explored on his own (1883-85); Franklin A. Nims and Robert Brewster Stanton of the Colorado River Survey (1889-90); Raymond Cogswell, who ran the Colorado River with Julius Stone (1909); the Kolb brothers (1911); and Eugene C. LaRue, who was the photographer of a U.S. Geological Survey expedition (1923). Of this wealth of photographic documentation, the most useful from the standpoint of interpreting desert vegetation are the many views taken by Nims and Stanton.

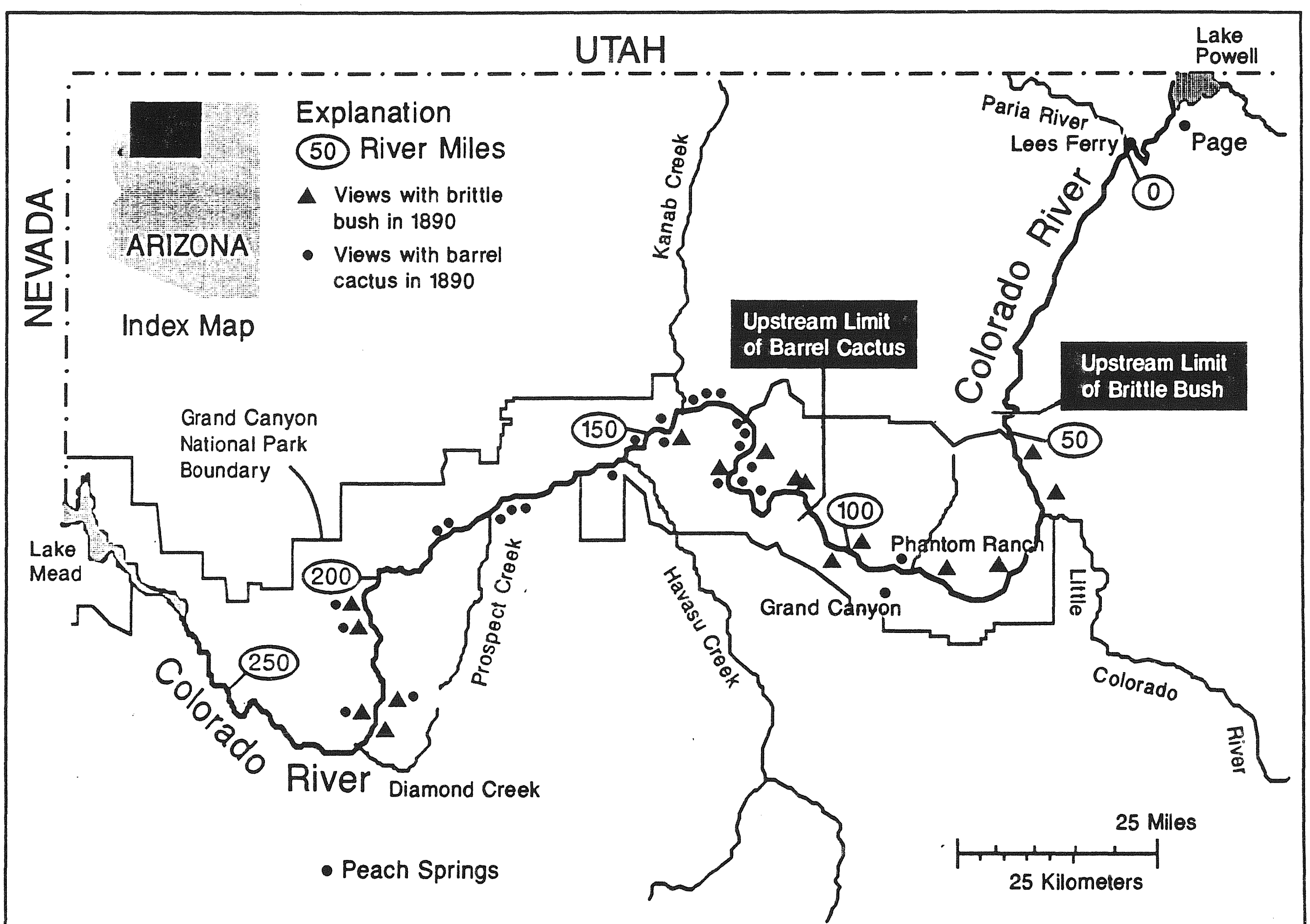

Figure 1. Map of the Grand Canyon.

Changes in Barrel Cactus

Barrel cactus *(Ferocactus cylindraceus,* formerly *F. acanthodes)* is common along the Colorado River between about mile 110 and Lake Mead. This cylindrical cactus, which is 1 to 3 meters tall, is readily identifiable in historical and modern views because of its shape and stature; we could discern individuals located as much 300 meters away from the camera station. The northerly limit of *F. cylindraceus,* like that of its congeners in the Mojave and Sonoran deserts, is determined by frost (Nobel 1980). Damage to chlorenchyma cells occurs at −8.4°C in plants that have been cold-hardened (Nobel 1982). Damage is minimized by spine coverage at the apex. Apical spine coverage increases somewhat with plant height, thereby increasing cold-temperature tolerance as the plants age (Nobel 1980). Adult plants are probably not at risk during extreme frost; instead, seedling and juvenile individuals are killed (Nobel 1984). Seedling establishment is also limited by prolonged drought (Jordan and Nobel 1981).

Like *Encelia, Ferocactus* appears to have been well established in its current distribution by 1890; Stanton first captured it about 32 kilometers downstream of the current upstream limit. Seeds of *Ferocactus* were found in packrat middens dated at 8,500 to 19,000 YBP that were collected at the western end of Grand Canyon (Phillips 1977). The most striking change shown in the replicated photographs is a dramatic increase in *Ferocactus* density along the entire river corridor. On average, 128 percent more individuals were visible in the 1990-1992 views than in the 1889-1890 views. In a paired-sample t-test comparison, the mean difference between 1889-1890 and 1990-1992 views was 7.9 individuals ($P < 0.000$). In 47 replicates showing *Ferocactus*, only 6 views from 1890 had more individuals than the 1990-1992 views. Although *Ferocactus* commonly appears in 1923 views, the density in 1923 was lower than in 1990-1992. As with *Encelia,* we suspect catastrophic frost drastically reduced the *Ferocactus* population sometime during the late 19th century. The absence of *Ferocactus* carcasses in the Stanton views suggests this occurred well before his 1890 expedition.

A comparison of replicated views shows that *Encelia* was well established by 1923, whereas *Ferocactus* was not. This lag in re-establishment may have resulted from their different reproductive strategies. *Encelia,* a prolific seed producer dispersed in part by wind, is well-suited for colonization of recently disturbed habitats or otherwise empty niches. Plants reach maturity at an early age, and, given a sequence of years favorable for establishment, populations can expand rapidly. In the vicinity of Tucson, Arizona, conditions favorable to *Encelia* germination occurred seven times between 1985 and 1992, a relatively frequent rate for a desert perennial (Bowers, unpublished data). *Ferocactus,* on the other hand, matures more slowly and produces fewer seeds, which are largely dispersed by animals. It encounters favorable germination conditions rather rarely, in only 8 of 18 years in the Mojave Desert (Jordan and

Nobel 1979). This species would, therefore, spread slowly from an initial occupation site.

Changes in Other Cacti and Succulents

Ten species of cacti were recorded in the Stanton views. Like *Ferocactus*, many of these are limited by frost, and, as would be expected, many have shown large increases during the past century. A second species of barrel cactus, *Echinocactus polycephalus*, was present at 23 camera stations in 1990-1992. Of these views, 13 from 1990-1992 showed *Echinocactus* whereas only 3 from 1890 showed it. At one site where *Echinocactus* was clearly visible, 3 individuals were present in the 1890 view (one persisted the century) whereas 11 new individuals were present in a 1991 view. Little is known of the environmental tolerances of *Echinocactus*, although it likely has tolerances similar to *Ferocactus*.

Among other succulents that have increased are *Opuntia erinacea*, *O. basilaris*, and *Echinocereus engelmannii*. Ocotillo (*Fouquieria splendens*), which occurs today between mile 157 and Lake Mead (Phillips *et al* 1987), is also limited in its northward distribution by low temperatures, but this species did not appear in enough views to make an adequate comparison of change.

Alternative Hypotheses for Observed Changes

It is possible that when Stanton traveled the Colorado River in 1890, *Encelia* and *Ferocactus* had only recently appeared in Grand Canyon. If so, the individuals shown in his photographs represent pioneers rather than relicts of formerly well-established populations. The absence of dead plants of either species is congruent with this hypothesis. Using photographs alone, we are unable to distinguish between pioneers and relicts; however, the scattered occurrence of both species along the river corridor in 1890 and preservation of evidence of these species in packrat middens as old as 19,000 YBP suggest the remnants of a decimated population rather than the forerunners of an advancing species. If the latter were the case, we would expect to see more plants in the downstream views than in the upstream ones, since downstream populations would have had more time for reproduction and establishment. Based on the limited number of photographs available, this does not seem to be the case.

Changes in climatic variables other than frost could have affected the density of *Encelia* and *Ferocactus* between 1890 and 1990. For example, extended summer drought could have reduced the density of *Encelia*. Yet, although the amount of summer precipitation in the region did decrease after 1942 (Hereford and Webb 1992), species that are more mesophytic than *Encelia*, particularly *Ephedra*, changed very little. Anomalously high rainfall is also a possibility (large floods occurred regionally in the late

1800s), but, again, other species that presumably would have responded favorably to the increased moisture were unchanged.

Anecdotal Evidence of Change in Frost Frequency

Grand Canyon forms a nearly ideal conduit for cold-air drainage during winter months on the Colorado Plateau. As a result, winter temperatures in the bottom of Grand Canyon are extremely variable. At Phantom Ranch, winter lows typically are above freezing but rarely approach –18°C. The lowest low temperature in the 20-year record at this station is –23°C, measured in January 1971 (Sellers *et al* 1985). At Lees Ferry, the lowest low temperature is –16°C, recorded in 1963. The low temperature of –14°C in January 1971 at Lees Ferry suggests the severe freeze recorded downstream at Phantom Ranch was somewhat localized. Low temperatures during the period around 1890 are unknown for these stations.

Instrumental weather records do not allow evaluation of frost frequency before and after 1890. Lees Ferry, Arizona, the longest record of relevance, began in 1916. Long-term records from the region are restricted, with perhaps the most appropriate being Fort Mojave, Arizona, which was established in 1863 about 200 kilometers southwest of Grand Canyon in the valley of the lower Colorado River. However, this site, near present day Bullhead City, was abandoned in 1938, which does not allow an evaluation of change in frost frequency. Anecdotal evidence is the only type of information available to verify a climatic change that is suggested by change in desert plants in Grand Canyon.

For the continental United States, average temperatures have increased since the 1800s (Kalnicky 1974). In the western United States, the late 1800s were characterized by periodic severe winters that may be related to anomalously frequent El Niño conditions, particularly between 1878 and 1891 (Quinn *et al* 1987). Between 1862 and 1910, abnormally large winter storms caused floods on most of the rivers in the southwestern United States (Webb 1985; Webb and Baker 1987); typically, such storms are followed by severe cold. On the Great Plains, the winter of 1886 claimed at least 35 percent of rangeland cattle during intense and frequent blizzards (Stegner 1953). In northern Nevada, half of the cattle died in the abnormally cold and snowy winter of 1889-1890 (Young and Sparks 1985). Stanton recorded this cold weather in his diary of the 1889-1890 Grand Canyon expedition (Smith and Crampton 1987).

One indication of the severity of winters in the late 1800s and early 1900s is the freezing of the Colorado River at Lees Ferry. Ferrymen, and later hydrographers, recorded freezes because of their effects on passage across the river or measurement of streamflow. The most severe documented freeze was in 1878, when the river was frozen from bank to bank below the Paria River for more than two weeks, allowing wagons to be driven across the river (LaRue 1925, p. 13). Other, less notable freezes of the river occurred in January of 1866, 1880, and 1925. The record of ice effects on the gaging station of the Colorado River at Lees Ferry (Figure 4) suggests a change in frost frequency at this site after the early 1930s that is coincident in a change from predominantly meridional to zonal flow over the Northern Hemisphere (Dzerdzeevskii 1969; Kalnicky 1974; Balling and Lawson 1982). Meridional circulation is required to advect arctic air masses into the Southwest.

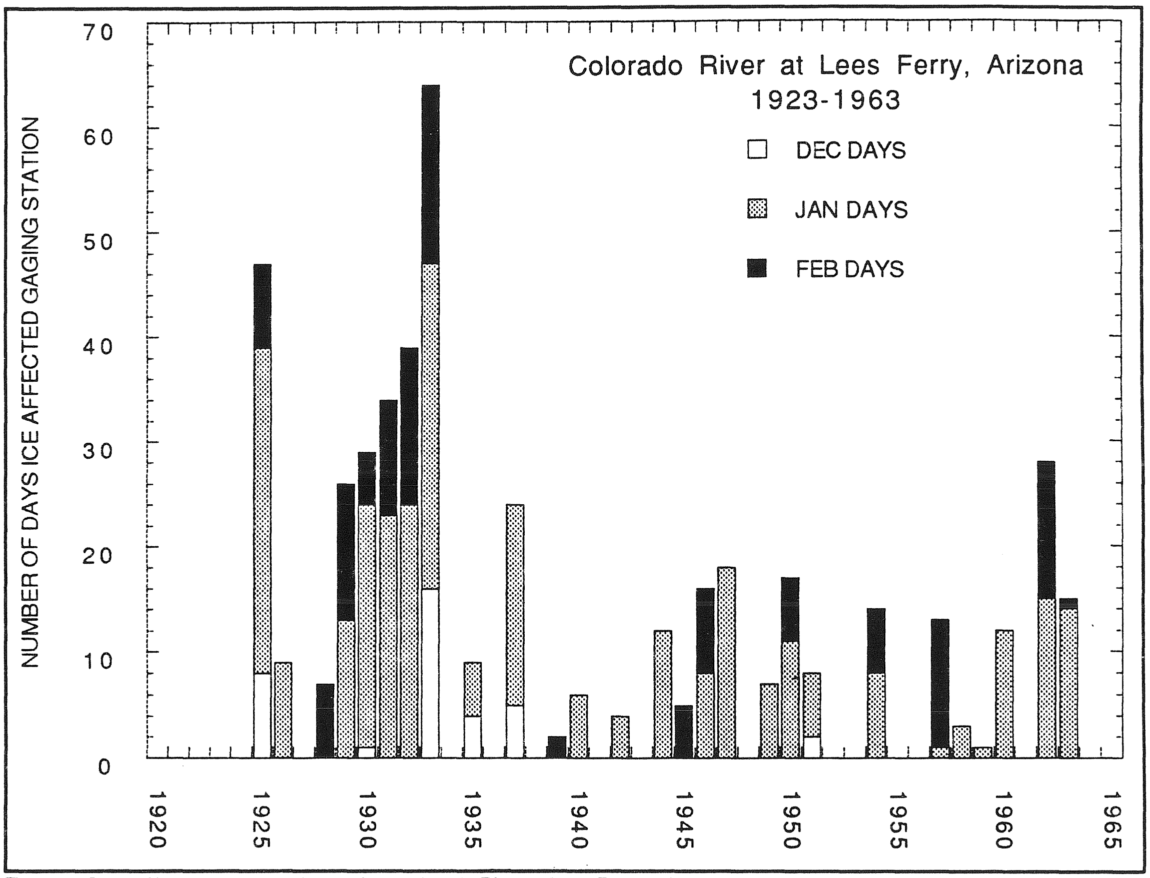

Figure 4. Days of ice at stream-gaging station, Colorado River at Lees Ferry, Arizona, 1923-1963.
Closure of Glen Canyon Dam in March 1963 ends this unique record. Data from annual reports on streamflow for the Colorado River basin (*eg*, U.S. Geological Survey, 1961).

Conclusions

In the last century, desert plant assemblages have changed significantly along the Colorado River in Grand Canyon National Park. The distribution and abundance of certain climatically insensitive species, such as *Ephedra*, have changed little. Most of the *Ephedra* individuals observed in the 1890 photographs have persisted throughout the intervening century. Other species, particularly *Encelia farinosa*, *Ferocactus cylindraceus*, and *Echinocactus polycephalus*, have increased in abundance since 1890. Occurrence of these species near their current distributional limits in 1890 indicates that they were suppressed sometime before that year; moreover, most *Encelia* visible in the 1890 photographs occurred on southerly-facing slopes or among groups of dark-colored boulders.

The suppression could have occurred during one event, such as the catastrophic freeze of 1878, but more likely the cause was a greater frequency of freezing weather than now occurs in Grand Canyon. Instrumental weather records do not exist for the critical period between settlement of the region and 1890; anecdotal evidence indicates the changes are related to a decrease in the frequency of severe frost after the turn of the century.

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