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Long-term change in perennial vegetation along the Colorado River in Grand Canyon National Park (1889–2010)

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Abstract: Long-term monitoring data are difficult to obtain for high-value resource areas, particularly in remote parts of national parks. One long-used method for evaluating change uses ground-based repeat photography to match historical images of landscapes. River expeditions that documented a proposed railroad route through Grand Canyon with large-format photographs occurred in 1889 and 1890. A total of 452 images from those expeditions are still in existence, and these were matched as closely as possible from December 1989 through March 1992. In 2010 and 2011, we are repeating these matches 120 years after the originals and 20 years after the first matches. This repeat photography provides visual information that can be interpreted for changes in terrestrial and riparian ecosystems along the river corridor, including change in the desert plant assemblages related to increasing winter low temperatures and severe drought. The riparian ecosystem, which originally consisted of native species established along the stage of frequent floods, has increased in area, density, and biomass as both nonnative and native species have become established following flow regulation by Glen Canyon Dam. The original and matched images provide the basis for one element of a robust monitoring program for the effects of climate change on ecosystem resources.

Key Words: climate change, Colorado River, dam effects, Grand Canyon, repeat photography, riparian vegetation

Introduction

Long-term monitoring data for perennial vegetation are difficult to obtain (Webb et al. 2009), particularly in remote terrain. Climate change and other anthropogenic influences have impacts on these isolated areas, and managers require scientific evaluations of landscape changes to make informed decisions about whether restoration or mitigation strategies are needed to ensure that resources remain intact for future generations. At the bottom of Grand Canyon (Arizona), the Colorado River winds about 450 km (280 miles) through a narrow, canyon-bound river corridor sustaining desert and riparian vegetation on substrates ranging from bedrock to river sandbars, creating a challenging environment for change-detection monitoring techniques (Belnap et al. 2008).

One method for evaluating change uses ground-based repeat photography to match historical images of landscapes (Webb et al. 2010). This technique, used worldwide to monitor environmental change, has a long history of application in Grand Canyon (Webb 1996). In the early 1990s, a unique set of images of the river corridor was used to document a variety of geomorphic and ecologic changes along the corridor of the Colorado River, including occurrence of debris flows that altered rapids, effects of feral burro grazing, longevity of desert shrubs, and notably influence of warming winter low temperatures on populations of frost-sensitive species (Webb and Bowers 1993; Bowers et al. 1995; Webb 1996). In 2010, 120 years after most of the original photographs were taken and about 20 years after the first series of matches, we revisited our camera stations in Grand Canyon National Park to further document changes in desert and riparian vegetation. Preliminary analysis of 151 new matches shows that original changes documented from 1990 to 1993 appear to be continuing, apparently showing the response of these ecosystems to climate change and river flow regulation.

Study methods

In 1889 and 1890, river expeditions led by Robert Brewster Stanton documented a proposed railroad route through Grand Canyon using large-format photographs (Webb 1996). A total of 452 images from those expeditions are still in existence. From December 1989 through March 1992, U.S. Geological Survey crews obtained high-quality original images and secured matches of all of them with large-format film cameras (Webb 1996). We matched the photographs from as close to the original camera station as possible using standard techniques employed by practitioners of the largest collection of repeat photographs (Boyer et al. 2010). In 2010, we obtained a second set of matches of 151 of the views 120 years after the originals and 20 years after the first matches, using the same techniques and cameras. Although all originals and matches are on film, they are digitized using professional-quality scanners for reproduction and analysis.

This repeat photography provides visual information that is interpreted for changes in terrestrial and riparian ecosystems along the river corridor, both at the camera station and afterward using digital imagery. Plants are identified on-site from the camera station within the field of view. For desert species, individual plants can be identified and compared using the geometry of outcrops and rocks in the original and matched images. Mortality and recruitment rates, expressed as percentage of plants per century, are determined through standard techniques (Bowers et al. 1995); for example, recruitment rate is $R = [N/(N + S)] \times [n/100 \text{ years}] \times 100\%$, where N = number of new individuals, S = number of surviving individuals, and n = number of years between photographs. For riparian vegetation, the high density of plants in the matched views hinders identification of some individual plants, but general changes in riparian vegetation at the species level can be determined using small areas of views where plants can be discerned. Biomass changes are visually estimated from the matched photographs as increased, about the same, or decreased.

Findings: Desert vegetation

For desert plant assemblages, repeat photography shows that the framework of the plant community, anchored by long-lived species such as Mormon tea (*Ephedra torreyana* and *E. nevadensis*) and creosotebush (*Larrea tridentata*), is extremely stable (fig. 1). Many species, notably creosotebush, Mormon tea, catclaw (*Acacia greggii*), mesquite (*Prosopis glandulosa*), and blackbrush (*Coleogyne ramosissima*), have individuals that live longer than a century (Webb 1996). Mormon tea and creosotebush individuals live much longer than 120 years and have low rates of mortality. Species-specific mortality rates (percentage of individuals lost per century) were 18% for Mormon tea and 7% for creosotebush (Bowers et al. 1995). Initial results of the second matching effort suggest that, in fact, mortality estimates for these species are high. Recruitment has exceeded mortality, with the net result that desert vegetation assemblages have shown a net increase in individuals. In addition, some species, especially creosotebush, have much larger individuals in the first and second matches (fig. 1), reflecting a general increase in biomass documented in most of the views.

We expected that the early 21st-century drought (Hereford et al. 2006), the most severe in a century, would result in widespread mortality of long-lived species. Our preliminary observations suggest, however, that few individuals of these species died in the two decades between the first and second matches. The ongoing severe drought that began in 2001 could represent future climate, and our preliminary results suggest that mortality of long-lived species will not increase. The effects of this drought, with its decreased winter precipitation, may be offset by normal or above-normal summer precipitation, which can be used by many species that also occur in the Sonoran Desert, or by increased water use efficiency resulting from the increased concentration of carbon dioxide.

Webb and Bowers (1993) and Webb (1996) proposed that a regional decrease in frequency of extreme freezes would lead to an increase in frost-sensitive species along the Colorado River. Barrel cacti (*Ferocactus eastwoodii*), which are common in western Grand Canyon, increased by an average of sixfold between 1890 and the 1990s, a result attributed in part to decreased frost frequency. Increases have continued in the initial matches from 2010 (fig. 1). Brittlebush (*Encelia farinosa*), another frost-sensitive species, increased substantially between 1890 and the 1990s, an expansion also attributable to a rise in low temperatures; our initial observations (fig. 2) suggest that brittlebush continues to expand at our photograph sites, contributing to the overall increase in apparent biomass.

Findings: Biological soil crusts

Biological soil crusts are communities of cyanobacteria, mosses, and lichens that dominate the soil surfaces of most desert regions (Belnap and Lange 2003), including those at Grand Canyon. These organisms are essential to the soil ecosystem, contributing stability; nutrients, especially nitrogen; and carbon. In Grand Canyon National Park, biological soil crusts at Stanton camera stations are especially well developed (i.e., have a high number of lichens and mosses) on limestone substrates, and moderately well developed on sandstone-derived soils. Soils derived from metamorphic rock have a low cover of lichens and mosses, but are still dominated by cyanobacteria. Crusts with more moss and lichen species contribute greater nutrients and stability than those with fewer species.

Biological soil crusts have low resistance to compression by feet or hooves, but they are extremely resistant to droughts. Repeat photography shows that where these communities are undisturbed by animals or humans, which is the case in most photos, there is almost no detectable change in extent or appearance of biological soil crusts (Webb 1996). In contrast, areas that overlook rapids or favorite visitation spots show a complete, or almost complete, loss of soil crusts to trampling (fig. 3). Trampling, however, generally left the framework of long-lived species intact, particularly Mormon tea, at least for the short term.

Findings: Riparian vegetation

Riparian vegetation documented in our repeat photography is sustained by the Colorado River, which has been regulated by Glen Canyon Dam since 1963. Flow regulation has reduced variability in flows, increasing discharge in formerly low-flow seasons and decreasing discharge during the early summer runoff period (Webb 1996). In response to these hydrologic changes, there has been a substantial change in distribution, abundance, and composition of riparian vegetation in Grand Canyon over the past 120 years. These changes are variable both in space and over time, ranging from imperceptible at some camera stations to striking state transitions at others; for example, some formerly bare channel bars and backwaters have been transformed into densely vegetated riverine marshes (fig. 2).

Less striking but related changes in riparian vegetation involve the structural simplification and mortality of mesquite and net-leaf hackberry (*Celtis reticulata*). Mesquite once dominated the old high-water zone (occurring at about the 2,830 m^3/sec flood stage [100,000 ft^3/sec]) but now occurs mostly well above the new riparian zone (at about the 850 m^3/sec [30,000 ft^3/sec] stage), although new individuals have become locally established. Net-leaf hackberry, less common, also is becoming established lower on once-barren channel margins. Whereas nonnative species like camelthorn (*Alhagi maurorum*), Bermuda grass (*Cynodon dactylon*), and tamarisk (*Tamarix ramosissima*, *T. chinensis*, and their hybrids; Friedman et al. 2005) comprise much of the novel assemblages of the new riparian zone, a diverse array of native woody riparian and herbaceous wetland species contribute to the mixture. The more common native species include coyote willow (*Salix exigua*), arrowweed (*Pluchea sericea*), seepwillow (*Baccharis salicifolia*), cattails (*Typha* sp.), common reed (*Phragmites australis*), and sedges. Goodding willow (*Salix gooddingii*) is restricted locally to certain sites.

Transformative changes observed in riparian vegetation in Grand Canyon are attributed to reductions in flood discharges and sediment load by Glen Canyon Dam operations. Reduced flow peaks, depleted of sediment, erode fine-grained bars, deposit coarser sand, and allow vegetation to encroach onto formerly active channel margins. Between 1890 and the 1990s, encroachment of woody riparian vegetation below the old high-water zone—primarily nonnative tamarisk—was expected because of regional trends. From the 1990s to 2010, more native species have become established in this zone. One important hydrologic change is the three short-duration prescribed dam releases with peak dis-charges of 1,100–1,350 m^3/sec (40,000–48,000 ft^3/sec) within the last 16 years (1996, 2004, 2008); these so-called habitat/beach-building floods were released in the winter-spring seasons when viable seeds of some native species, but not nonnative tamarisk, were present.

The spatially rich collection of historical photos from the Stanton expedition, along with precise matches in the early 1990s and 2010, indicate that a more nuanced view of riparian vegetation change along the Colorado River is needed. Encroachment of vegetation over the past two decades onto depositional surfaces that had remained unvegetated until the early 1990s suggests that there are a range of hydrogeomorphic environments that have responded, and may continue to respond, to subtle changes in flow management in the postdam period. Despite relatively large dam releases, in the postdam perspective of flood control, colonization of low-stage habitat continues, creating a much more diverse riparian assemblage than was present in the 1990s. This is consistent with a growing body of evidence that measurable shifts in riparian vegetation accompany modest climate-related shifts in flow regime for rivers across the Colorado Plateau that are less intensely regulated than the Colorado River (Allred and Schmidt 1999; Birkeland 2002).

Conclusions

Repeat photography in Grand Canyon documents long-term change caused by a variety of processes, ranging from climate change to visitor impacts and the influence of Glen Canyon Dam. In the zone of desert plants above the direct influence of the Colorado River, a framework of long-lived shrubs and small trees with life spans exceeding a century survived the extreme early 21st-century drought, but is changing with the addition of frost-sensitive species, mostly cacti and brittlebush. The riparian zone continues to respond to changes brought about by operations of Glen Canyon Dam, including flood control, changes in seasonality of large dam releases, and depleted sediment supply. The net result in both desert and riparian ecosystems is an increase in apparent biomass on the landscape. The original and matched images along the Colorado River provide the basis for one element of robust monitoring for the effects of climate change on ecosystem resources in Grand Canyon National Park.

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R. B. Stanton, 57-RS-619

Figure 1 (all three photos in this sequence). Lava Falls Rapid, mile 179.3, view upstream from river left.

Photo A (this photo). (27 February 1890). Facing away from the commanding view of Lava Falls Rapid, Robert Brewster Stanton took this upstream-looking photo, showing desert vegetation in the foreground and the river channel in the mid-ground. Creosotebush (*Larrea tridentata*) is the dominant shrub, and five barrel cacti (*Ferocactus eastwoodii*) and one Mormon tea (*Ephedra nevadensis*) are present; this group is typical of the Mojave Desert assemblages of western Grand Canyon. The channel banks are barren below a line of riparian vegetation, likely dominated by mesquite (*Prosopis glandulosa*), that occurred at about the 2,830 m^3/sec (100,000 ft^3/sec) flood stage.

Compare with:
Fig. 1B

Fig. 1C

R. B. Stanton 57-RS-396

Figure 2 (all three photos in this sequence). View upstream showing Cardenas Marsh, mile 71.3.
Photo A (this photo). (23 January 1890). Stanton took this upstream-looking photo from a hillside below the Cardenas Hilltop Ruin, a prominent archaeological site in the Furnace Flats reach of Grand Canyon National Park. Except for scattered mesquite and what may be clumps of coyote willow (*Salix exigua*), little riparian vegetation is present along the Colorado River. Numerous backwaters occur in this reach, including the prominent complex at right center. The foreground slopes sustain an assemblage of desert vegetation, including Mormon tea (*Ephedra torreyana*), Anderson thornbush (*Lycium andersonii*), and big galleta grass (*Pleuraphis rigida*).

Compare with:
Fig. 2B
Fig. 2C

R. B. Stanton, 57-RS-477

Figure 3 (all three photos in this sequence). Crystal Rapid, mile 98.2, view upstream from river right.

Photo A (this photo). (8 February 1890). When Stanton captured this view looking upstream from what is now known as the right scout point of Crystal Rapid, there was considerable sand among the boulders covered with dense biological soil crust. This high debris fan, probably an Early Holocene relict, was stable with a mature desert vegetation assemblage dominated by Mormon tea and perennial grasses.

Compare with:
Fig. 3B
Fig. 3C

Ralph Hopkins

Figure 3 (all three photos in this sequence). Crystal Rapid, mile 98.2, view upstream from river right.

Photo B (this photo). (1 February 1990). A century later, the foreground shows the effects of trampling from river runners visiting the prominent scout point for Crystal Rapid. Most Mormon tea present in 1890 persists, although the biological soil crust and perennial grasses are victims of foot traffic. Catclaw (*Acacia greggii*) and goldenbush (*Isocoma acradenia*) either have become established or are more clearly identifiable. The foreground surface has eroded in response to trampling, as evidenced by additional exposure of rocks. Sandbars in the distance have deflated or at least are less obvious because of the establishment of nonnative tamarisk.

Compare with:
Fig. 3A
Fig. 3C

Tom Wise

Figure 2 (all three photos in this sequence). View upstream showing Cardenas Marsh, mile 71.3.
Photo B (this photo). (26 February 1993). The marsh at the mouth of Cardenas Creek (center mid-ground) is nesting habitat for southwestern willow flycatchers, an endangered species. Most of the increased riparian vegetation in the marsh and elsewhere is tamarisk, although Goodding willow (*Salix gooddingii*), coyote willow, arrowweed (*Pluchea sericea*), and other native species have increased as well. The mesquite persistent from 1889 has died back because flow regulation has reduced the size of floods providing necessary water. The backwaters in the view are reduced because of sediment deposition and tamarisk encroachment. In the desert vegetation of the foreground, five individuals of Mormon tea, seven of Anderson thornbush, and three of big galleta grass have survived the 103 years between the original and matched photographs. Brittlebush (*Encelia farinosa*) appears in the view as globose gray-green shrubs and was not present in 1890.

Compare with:
Fig. 2A
Fig. 2C

R. H. Webb

FigFigure 1 (all three photos in this sequence). Lava Falls Rapid, mile 179.3, view upstream from river left.

Photo B (this photo). (11 February 1990). Most of the creosotebush have persisted in the intervening century since the first photo was taken, as has one individual Mormon tea. While none of the original barrel cacti have survived, the number of individuals has more than tripled to 17, and beavertail pricklypear (*Opuntia basilaris*), Engelmann pricklypear (*Opuntia engelmannii*), and cholla (*Cylindropuntia whipplei*) are now present. We attribute these changes to decreased frequency of severe frost events. Tamarisk (*Tamarix* spp.) and mesquite are prominent along the river corridor.

Compare with:
Fig. 1A
Fig. 1C

William Lemke, Stake 1510c

Figure 1 (all three photos in this sequence). Lava Falls Rapid, mile 179.3, view upstream from river left.

Photo C (this photo). (27 September 2010). Most of the creosotebush have persisted 120 years through this photographic record, which includes other matches made in 1993 and 2003 (not shown). Several barrel cacti present in 1990 have died, probably during the early 21st-century drought, but new replacements increase the number in the view to 22; pricklypear and cholla have also increased in a continuing response to warming winter conditions. Riparian vegetation, leafed out in this image, has increased in the intervening 20 years.

Compare with:
Fig. 1A
Fig. 1B

William Lemke, Stake 1440

Figure 2 (all three photos in this sequence). View upstream showing Cardenas Marsh, mile 71.3.
Photo C (this photo). (20 September 2010). A large open sandbar extends downstream from Cardenas Marsh, but this probably resulted from seasonal deposition of sand from the Little Colorado River upstream and likely will not persist. The Goodding willows in the Cardenas Marsh have crown dieback, suggesting that early 21st-century low-flow conditions may be impacting native species here. Mesquite on the sand dunes behind the marsh appear to be dying or dead as a result of continued flow regulation. Brittlebush is now the dominant shrub on the foreground hillslope, a change we attribute to warming winter conditions. Anderson thornbush continues to persist, but one of the two Mormon teas that persisted until 2003 has died.

Compare with:
Fig. 2A
Fig. 2B

William Lemke, Stake 1468

Figure 3 (all three photos in this sequence). Crystal Rapid, mile 98.2, view upstream from river right.

Photo C (this photo). (22 September 2010). Many Mormon teas survived the intervening 120 years, particularly the one in the right foreground, although perennial grasses that once grew here have not reestablished and biological soil crusts continue to be trampled. Tamarisk, which is leafed out and hence more visible than in 1990, appears to have grown larger.

Compare with:
Fig. 3A
Fig. 3B

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